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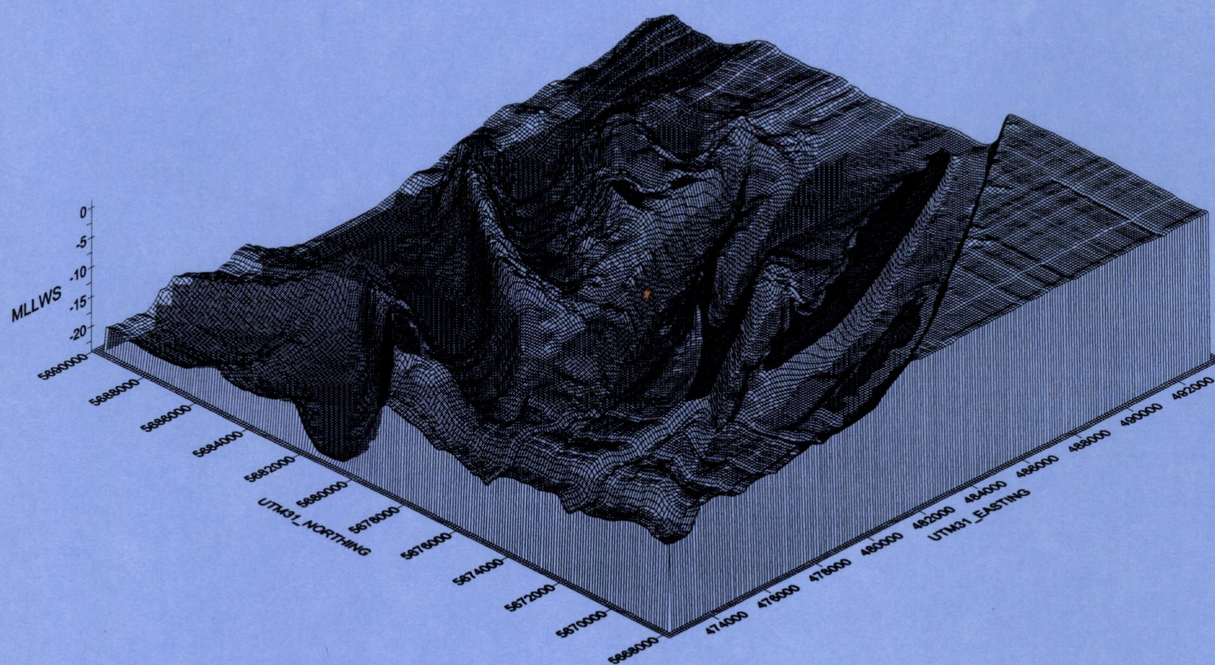
Sediment and morphodynamics of a siliciclastic near coastal area, in relation to hydrodynamical and meteorological conditions: Belgian continental shelf

De sediment- en morfodynamiek van de kustnabije zone in relatie tot de impact van hydrodynamische en meteorologische factoren in een silicoclastische omgeving, Belgisch continentaal plat



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Abstract

De Belgische kustnabije zone wordt gekenmerkt door een aantal zandbanken die nagenoeg parallel aan de kust verlopen. In het kader van deze studie werd de sediment- en morfodynamiek bestudeerd van de Stroombank, de Nieuwpoort Bank en de Baland Bank en werd een vergelijkend onderzoek verricht langsheen de zuidelijke rand van de Vlaamse Banken.

Teneinde het sedimentologisch en morfologisch gedrag van een macrotidaal ondiep-water kustsysteem (-5 tot -15 m GLLWS) te bestuderen, werd een geïntegreerde onderzoeksmethodologie opgesteld en dit voor verschillende ruimte- als tijdschalen.

Sedimenttransportberekeningen toonden aan dat de getijdestromingen competent genoeg zijn om het *in-situ* sediment in beweging en in suspensie te brengen.

Uit de sedimentaire opbouw van het gebied bleek dat de oppervlakkige sedimenten vooral gekenmerkt zijn door fijn tot heel fijne zanden. Opmerkelijk is de correlatie van grovere zanden (> 250 µm) met het voorkomen van grotere bodemstructuren. Sedimentatie van slib kan verwacht worden dieper dan ruwweg -6 m.

Een interactief model wordt voorgesteld ter aanduiding van het behoudsmechanisme van het zandbanken – geulen systeem. Hieruit bleek dat de grovere sedimentfracties zich bevinden aan de basis van de zandbanken resulterend uit een aanrijkingsproces vanuit de geulen. Deze sedimentbuffer wordt hydraulisch gesorteerd en geleidelijk hellingopwaarts getransporteerd door de gecombineerde actie van getij en golven. Deze processen bleken geldig onder veranderende weersomstandigheden.

Windaangedreven stroming is belangrijk in de kustzone. Algemeen gesteld komen de laagste sedimentvolumes overeen met zomer en herfst condities, terwijl de wintermaanden het hoogste volume vertonen en gekenmerkt zijn door een aanrijking van fijnere zandige sedimenten. Versterking van de getijdestroming door meteorologische invloeden in een zelfde richting verhoogt aanzienlijk het sedimenttransport. Uit de temporele metingen bleek tevens dat de duur en de uniformiteit van de meteorologische factoren primeert boven hun sterkte. Het gebied kent een vlug herstel.

Uit de spatiale en temporele differentiatie van het kustsysteem blijkt dat het sedimenttransport langsheen goed afgelijnde transportpaden verloopt. De nabije kustzone is dan ook aanzien als een auto-regulerend sedimenttransportsysteem waarbij een transversaal transport ondergeschikt is aan het kustlangse transport.

Het lijkt aannemelijk dat de kustbanken gevormd zijn onder een hydraulisch regime gelijkaardig aan het hedendaags systeem.

The Belgian near coastal area is characterised by shallow marine sandbanks lying more or less parallel to the shoreline. Research activities were focussed on the sediment- and morphodynamics of the Stroombank, the Nieuwpoort Bank and the Baland Bank, supplemented by a comparative investigation along the interaction zone with the Flemish Bank system.

To study the sedimentological and morphological behaviour of this macrotidal environment (-5 to -15 m MLLWS) an integrated research strategy was set up covering different spatial as well as temporal scales.

Sediment transport calculations showed that the tidal currents are generally competent enough to resuspend the in-situ sediments.

The surficial sediments of the near coastal zone are mainly characterised by fine to very fine sands. Still, medium sands occur in the areas witnessing an intense tide-topography interaction. Striking is the correlation with the presence of bedforms. Deeper than roughly -6 m the surficial sediments are most likely enriched with mud.

An interactive model is proposed whereby the transport of sediment is mainly dependent on the swale configuration. Especially when the tidal currents are funnelled, sandy deposits are being washed out and stored along the slopes of the banks. Part of the accumulated sediments is subsequently winnowed out and transported upslope the sandbanks by the combined action of currents and waves. In time, the above mentioned observations and interpretations can be confirmed.

From the chronosequential measurements an indication could be given of the vulnerability of the coastal system. It can be stated that there is a clear relation between the observed morphological changes and the ruling hydro-meteorological conditions. Generally the lowest sediment budgets correspond with summer and autumn conditions, whilst the winter months witness the highest sediment volumes and are characterised by an abundance of fine sandy sediments. Sediment transport is most intense when the direction of storminess parallels with the configuration of the swales. From the observations, it can also be deduced that the duration of stormy conditions is more important than the strength. Moreover, the sedimentary pattern in the near coastal area is characterised by a quick recovery after stormy periods.

From the spatial and temporal differentiation, the near coastal area can be regarded a self regulating sediment transport system dominated by longshore sediment fluxes.

The origin of the Coastal Banks is likely constrained to a time period having hydrodynamic characteristics comparable to the nowadays situation.

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Gent, May 1999

1. INTRODUCTION

1.1. General framework

Studying the dynamics of a coastal system can undoubtebly be related to coastal erosion and accretion phenomena. The latter are most persistent along the coast; inevitably, coastal erosion is one of the key issues in coastal zone management. The variability and natural constraints of a coastal system often inhibit a thorough investigation of the processes involved, and are in terms of geosciences perhaps the most poorly understood and imperfectly documented part of a country. Moreover, the management of a marine environment should be seen in a holistic perspective where integrated knowledge is a necessity.

On a Belgian level, a lot of effort is invested in a general consensus regarding the policy for the coastal zone. The management plan "Kust 2002" (MINISTERIE VAN DE VLAAMSE GEMEENSCHAP (1993)) aims mainly to ensure an optimal security level, but is also a guarantee to protect the social, economical, touristical and ecological values of our coastal patrimony. The need for detailed studies is one of the items put forward as a priority. The legislature around coastal erosion and coastal protection is also discussed in DE PUTTER & al (1993), DE WOLF et al. (1993) and DE WOLF (1994).

One of the main issues is the need for integration of data. Given the limited coastal stretch and the available means for its investigation, a wealth of information is available. However a global view is missing due to a lack of relations between conducted studies. The latest years more and more emphasis is put on the "*design with nature*" principle which implies that a thorough understanding of natural processes and knowledge of their causal mechanisms is of primary importance (GAO & COLLINS (1995)). Coupled to hydrodynamical and meteorological data, this strategy provides a tool for the evaluation and prediction of the risk status.

From a scientific perspective the research can be viewed in the framework of the investigation of sediment and morphodynamics, more specifically related to sandbanks. On the Belgian continental shelf a lot of research has been done on the dynamical behaviour of the more offshore Flemish Banks (Fig. 1.01). However, the zone between nearshore and offshore is far less investigated. Studies conducted by VAN VEEN (1936), BASTIN (1974), GULLENTOPS et al. (1977), DE MOOR (1986a), DE MAEYER & WARTEL (1988) have a more global perspective, but apparently an investigation of the spatial and temporal behaviour of morphological entities is still missing. To the nearshore, detailed studies are in general concentrated around the harbour of Zeebrugge (e.g. MALHERBE (1991)) or are confined to specific problem situations (e.g. intense erosion around De Haan (Fig. 1.01)).

On a European level, research stimulated and funded by the MArine Science and Technology (MAST) programmes showed a major breakthrough for multidisciplinary investigation. Within the MASTI – Resecused "*Relationship between Seafloor Currents and Sediment Mobility in the Southern North Sea*" project, the natural behaviour of the Middelkerke sandbank was studied genetically as well for its sediment- and morphodynamics (DE MOOR & LANCKNEUS (1993)). MASTII – Starfish "*Sediment Transport and Bedform Mobility in a Sandy Shelf Environment*" extended the monitoring of the Middelkerke Bank, but concentrated more on the parameterisation of physical processes governing morphological change (HEYSE & DE MOOR (1996)). Moreover, a study of the sediment interactions between beach, nearshore and offshore was envisaged. MASTII - CSTAB "*Circulation and Sediment Transport Around Banks*" (O'CONNOR (1996)) was confined to the quantification of the role played by nearshore linear sandbanks on both nearshore processes and adjacent beaches and coastlines. The behaviour of a coastal system, especially the cross-shore sediment exchange between nearshore and offshore is also important in the perspective of shoreline stability and sea level rise (WIERSMA & VAN ALPHEN (1988)).

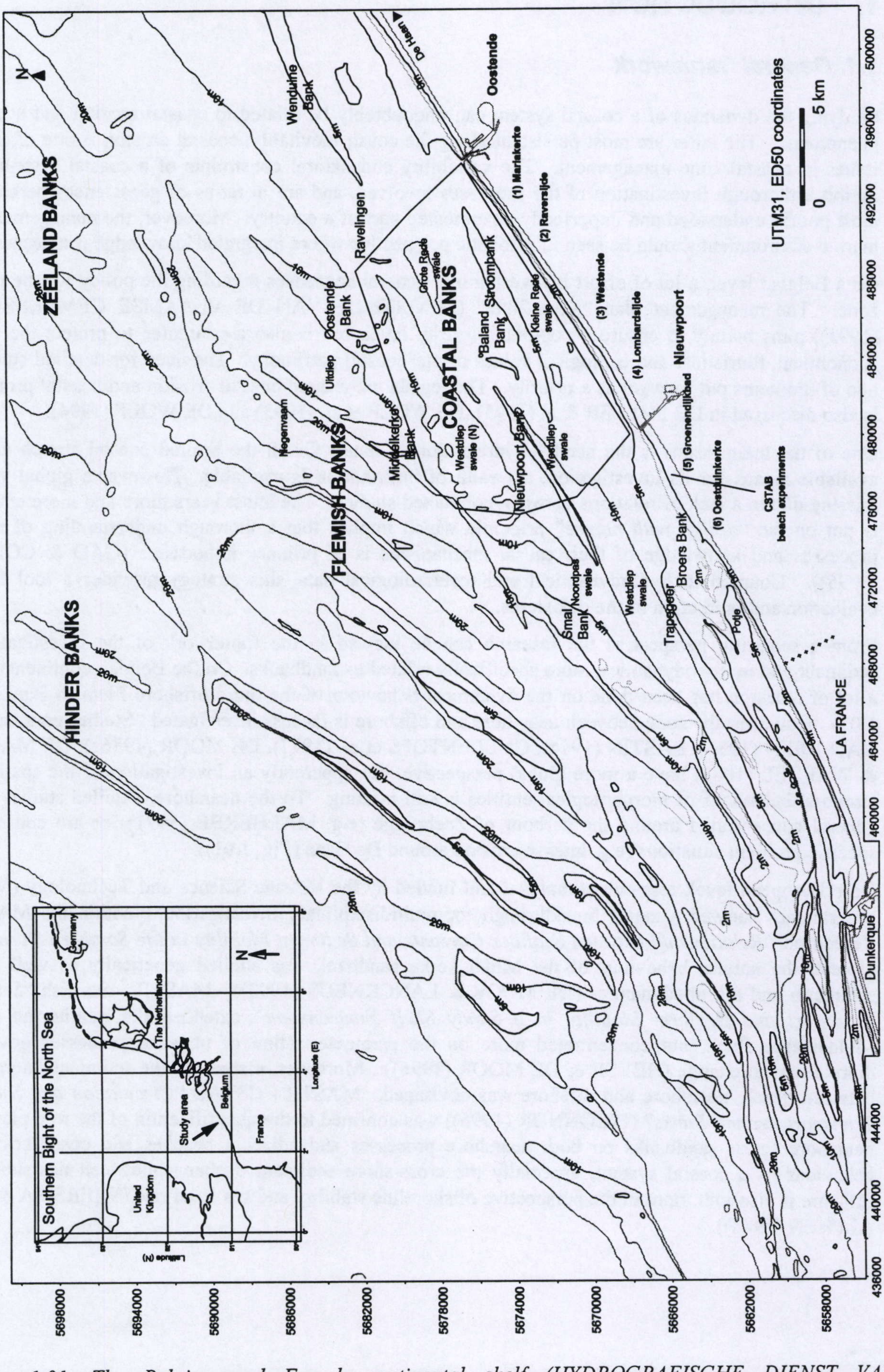

Figure 1.01 – The Belgian and French continental shelf (HYDROGRAFISCHE DIENST VAN OOSTENDE AFDELING WATERWEGEN KUST (1995)).

The nature and behaviour of sandbanks and its superimposed bedforms in relation to the forcing hydrodynamical and meteorological agents is still one of the key elements in coastal research. Especially the physical behaviour of large compound dunes having a complex morphology comprising ripple-like structures is still open for discussion. Quantitatively, questions arise regarding the amount of sediment involved and the velocity of their movement. Moreover, these issues are of primary importance for the exploitation of sandy aggregates, which can also have implications on coastal erosion phenomena (HARRIS et al. (1990)).

Sandbanks may form a morphodynamic system provided sufficient sand is available and hydrodynamic processes are capable of moving sediment. Such a system is dynamic as there is a close coupling and feedback between hydrodynamic forces, sediment transport and morphologic change, continuously striving to an equilibrium state (WRIGHT & THOM (1977)). The morphodynamic behaviour of such sandbank systems has received much attention, from as well modelling studies (ZIMMERMAN (1981); HUTHNANCE (1982a); HUTHNANCE (1982b); BOCZAR-KARAKIEWICZ & BONA (1986); DE VRIEND (1990); BOCZAR-KARAKIEWICZ et al. (1990); BOCZAR-KARAKIEWICZ et al. (1991); HULSCHER et al. (1993)) as from observational studies (HOUBOLT (1968); SWIFT et al. (1972); SWIFT & FIELD (1981); HEATHERSHAW & HAMMOND (1980); PATTIARATCHI & COLLINS (1987)). However, a lot of debate exists on determining which processes govern their formation and which are responsible for maintaining their equilibrium. The sandbanks may have a relict origin, while the present regime may have turned them into a morphodynamic system (FIELD (1980)).

Near coastal sandbanks are very effective in protecting the coast as they dissipate energy from incoming waves (CARTER & BALSILLIE (1983)). In the coastal area off Nieuwpoort – Oostende, MACDONALD & O'CONNOR (1996) numerically modelled the variations in wave energy according to sea level rise. Testing several wave conditions and sea level rise scenarios, they predicted that the average wave energy impacting on the coast increases in the order of 10 % by the year 2130. Model results show that removal or lowering of the banks will lead to an increase in the incident wave heights, and the existing balance between accretion and erosion will be tilted towards the latter, causing the coastline to recede. Clearly this demonstrates that a thorough understanding of coastal processes is of primary importance in coastal zone management.

The current research can be seen as an extension of the efforts made within Starfish and CSTAB, but will be more concentrated on the spatial and temporal variability of the physical functioning of a coastal system in which the interaction of sandbanks and swales predominates.

1.2. The Belgian Coastal Zone

1.2.1. General outline

The Belgian continental shelf is for a large part covered by sandbanks that are grouped as *Coastal Banks, Flemish Banks, Zeeland Banks* and *Hinder Banks* (Fig. 1.01). Given their unique configuration and pronounced morphology, the Flemish Banks are most known in literature (i.e. VAN VEEN (1936); HOUBOLT (1968); DE MOOR (1985); HOUTHUYS (1990); LANCKNEUS et al. (1994)). The present research is confined to the coastal system, landward constrained by the - 6 m contour line between the cities Nieuwpoort and Oostende, seaward by the Flemish Banks. The Nieuwpoort Bank and Stroombank, both lying parallel to the coastline, are the main morphological entities.

The sandy and 65 km long rectilinear Belgian coast borders the southern North Sea in a SW-NE direction and merges eastward into the Westerschelde, a 5 km wide estuary with little river outflow, but nonetheless a large tidal exchange (DE MOOR (1988)). The mean amplitude of the semi-diurnal tide reaches about 4 m, decreasing by 0.5 m from west to east. Prevailing winds and waves from SW to NW direction and the dominant NE directed flood tidal current provoke a residual littoral drift in a northeastern direction. As a consequence of the dominant wind direction, also an aeolian drift in easterly direction occurs. Fetches of more than 200 km can only be attained from the north, implying that storms from north-western to northern direction are the most devastating ones (MINISTERIE VAN DE VLAAMSE GEMEENSCHAP (1993); DE MOOR (1988)).

On the basis of tide gauge measurements at Oostende (from 1835 to 1852 and from 1927 to 1988) BAETEMAN et al. (1992) defined a present-day rate of mean sea-level rise of 0.01 m/decade. Sea-level movements in the French-Belgian coastal plain during the past 2500 years have recently been studied by LOUWYE & DECLERCQ (1998).

Beach and foreshore are studied using remote sensing and air cushion bathymetry in combination with beach profiling (DE WOLF et al. (1993), KERCKAERT (1989)). However, the extensive monitoring is restricted to an area up to 1500 m offshore corresponding to a depth of about -6 m MLLWS (from +5 m on land).

The macrotidal sandy beaches are gently sloped and are characterised by a typical ridge-and-runnel morphology. The width of the beaches varies from 600 m near the French border and Oostduinkerke to 200 m towards the east. Beach profiling along the Belgian coast over a period of several decades revealed several sections with long-term residual erosion or accretion. Some of them can be related to coastal management, others however are of a natural origin. From volumetric time series DE MOOR (1979, 1985, 1992) puts forward a semi-qualitative model of spatially and temporally alternating erosive and accumulative phases which he called respectively "erosive and accumulative megaprotuberances". Today more than 70 % of the Belgian coastline is defended by soft or hard defence structures, mostly longshore seawalls, groynes as well as through beach scraping and nourishment. Subaquatic nourishment through feeder berms is carried out along the most erosive coastal section Oostende – De Haan (MINISTERIE VAN DE VLAAMSE GEMEENSCHAP (1993); CHARLIER & DE MEYER (1995)).

The natural sea-defence of the coastal lowlands is still represented by the dune belt reaching elevations of 15 to 25 m and a width varying from 2 km in the westernmost and easternmost parts to hardly 100 m in the central part of the dune area.

The Belgian coastal plain was formed during the Holocene in a wave/tide-dominated environment and is at present 15 km wide. In the west, the plain is crossed by the river IJzer, along which the plain extends up to about 20 km. However it appears that this river provided no significant sediment supply to the area throughout the Holocene (BAETEMAN & DENYS (1997)). The coastal plain corresponds to a marshland of Dunkerquian age, which developed behind a more or less closed coastal barrier. The tidal flats were reclaimed between the 9th and the 13th century. Nowadays the 'polder' level varies from 0 to 5 m above the mean spring low water level. A distinct microrelief can be noticed as a consequence of differential sedimentation and different settling induced by reclamation and drainage (DE MOOR (1988). MARECHAL (1992), DE MOOR & PISSART (1992)). A synthesis of the evolution of the Holocene Belgian Coastal Plain was elaborated by DE MOOR (1986b), DE MOOR (1988), BAETEMAN (1993), BAETEMAN & DENYS (1997). HOUTHUYS et al. (1993) published a comparative synthesis of the development of the Holocene coastal plain in Belgium and Northern France. A geomorphological map of the area Nieuwpoort – Oostende covering the coastal plain has been published by DE MOOR et al. (1993).

1.2.2. Anthropogenic influences

Given a limited coastal stretch of only 65 km, a strong urbanised coast seems inevitable. As mentioned before, most of the beaches are heavily groyned and/or are maintained artificially (MINISTERIE VAN DE VLAAMSE GEMEENSCHAP (1993)). Seaports and navigation channels are continuously dredged (MINISTERIE VAN DE VLAAMSE GEMEENSCHAP (1994)) and some parts of the offshore Flemish and Zeeland Banks are subject of aggregate extraction (MINISTERIE VAN ECONOMISCHE ZAKEN (1999)). However, in the following paragraph, only the dumping of dredged material will be briefly outlined as these activities were thought to have an impact on the study results.

Along the Belgian coast, more specifically in the seaports and navigation channels, on average 25 million m^3 of dry material is dredged on a yearly basis (MINISTERIE VAN DE VLAAMSE GEMEENSCHAP (1994)). Since 1984 those dredging operations are being optimised, and the dispersion and recirculation of fine-grained sediments (being a mixture of fine sand and mud) is intensively studied, which in turn leads to a better evaluation of the ecological impact of such activities (MINISTERIE VAN DE VLAAMSE GEMEENSCHAP (1994)). An overview of research using mostly engineering and sedimentological tools can be found in DE MEYER & MALHERBE (1987), MALHERBE (1991) and MINISTERIE VAN DE VLAAMSE GEMEENSCHAP (1994). Hydraulic segregation mechanisms were identified showing a clear separation of a less mobile sand fraction and a highly mobile muddy fraction, which is consequently easily recirculated.

DE MEYER (1994) investigated the behaviour of dredged material under natural circumstances using radioactive tracer experiments and a global sediment trend analysis (McLAREN & BOWLES (1985)), based on a numerous amount of grab samples spread over the Belgian continental shelf. Results showed that the Belgian coastal zone, more specifically up to 5 km offshore in the West and up to 20 km in the East, is primarily influenced by transport of sediments in a coastward direction (DE MEYER (1994)). Within that area, recirculation of fine-grained material is very important and will only be deposited in areas of hydrodynamic equilibrium, being in most case harbours and navigation channels. Moreover, MALHERBE (1991) identified a turbidity maximum area east of Zeebrugge, which controls sediment accumulation in the harbours and navigation channels. The muddy deposits seem to be hydraulically trapped whereby an interaction exists of a loosely packed sediment layer and a suspension load. Tracer experiments (MALHERBE (1991)) highlighted that only 0-40 % of the dumped material remains at the site (mostly fine sand), whilst the muddy fraction disperses over a large area being concentrated as narrow loosely packed bottom layers that migrate along the Belgian Coast.

The spatial and temporal variation of suspended load throughout a tidal cycle has been qualitatively and quantitatively studied through an integrated approach using calibrated digital multispectral airborne scanner registrations in combination with in-situ sampling at 1 m below the sea surface (FRANSAER (1994)). In order to obtain an empirical relation of suspension and sedimentation of the mud (fraction less than 63 μm), the results of the experiment were combined with a detailed numerical model taking into account velocity gradients and tidal variations along the Belgian Coast.

The resulting "mud charts" clearly confirm the presence of a turbidity maximum area roughly between Oostende and Zeebrugge. During the experiments the amount of mud reached about 134.000 ton meaning that taking into account an area of about 158 km^2 and a mass density of 1.200 kg/m^3, an upper mud layer of about 5 mm is continuously moving, up to distances of about 7 km. In time, this zone shifts in position and magnitude, but reaches a maximum spreading respectively just before high water and low water. At the turning of the tides the suspension cloud is completely vanished meaning that most of the muddy fraction settles out. This observation is confirmed by several measurements during different circumstances, and leads to the conclusion that flocculation and sedimentation out of surficial waters are fairly rapid processes and are continuously reworked both by natural and artificial processes. Moreover, no important sediment exchange with offshore areas seemed to exist.

1.3. Comparison with other coastal systems

As the dynamics of a coast is a phenomenon that is not bound by any political constraint, a coastal system should be seen in a broader framework. An obvious comparison can be made with coastlines lying adjacent to the Belgian coastal zone. In the following paragraphs, a short overview will be given of the characteristics of the French and Dutch coast respectively.

In the framework of a multidisciplinary study CORBAU et al. (1993), CORBAU et al. (1994) and CORBAU et al. (1999) investigated the sedimentary development of a littoral zone, extending from the western part of the harbour of Dunkerque up to the France – Belgium frontier. The area, approximately 35 km long and WSW-ENE oriented, is characterised by semi-diurnal tides having a tidal range of 5 m and velocities over 1 m/s in the dominant flood direction (NE). Incident wave angles are mainly SW-WSW, N-NNE oriented. Storm swells have a N to NW fetch direction. The fine sandy beaches are about 300-500 m in length, backed up by a dune belt of 750 m in width and 10-15 m in height. The intertidal area typically consists of an alternation of sandy bars and troughs parallel to the coastline. Offshore, a complex of sandbanks forms the southern part of the Flemish Banks (BECK et al. (1991)). The most landward trough is the access channel to the port of Dunkerque. Surficial sediments are fine and homogeneous on the banks and on the shoreface, whilst coarser sediments characterise the swales. Since 1740, the zone east of Dunkerque is suffering from erosion at a global rate of 1 m/yr. However at some locations, phases of erosion seem to alternate with accumulation, enhanced by a shoreward displacement of the offshore sandbanks. On a timespan of a few years beach and offshore are more or less in a dynamical equilibrium. Net erosion along the region bordering the Belgian coastal zone can be observed, which can be related to a concentration of wave energy. Wave action is held responsible for a shoreward migration of the banks (1-5 m/yr), whilst tidal currents try to maintain their morphology through sand supply.

North of Belgium, the Dutch coastline extends over a length of 432 km, consisting for 82 % of sandy beaches characterised by fine- to medium-grained quartz sand (EISMA (1968), SHORT (1992)). About 40 % of the beaches are defended by groynes or pile rows, especially in the Delta area and in the southern and northern parts of the Coast of Holland. The tidal regime is characterised by a micro- (0-2 m) to mesotidal (2–4 m) range (HOEKSTRA & STOLK (1992)). Along the Holland Coast, flood currents to the north attain maximum values of about 0.8 m/s at spring tide, whereas the south-oriented ebb currents have a maximum of 0.7 m/s resulting in a residual current to the northeast (WIERSMA & VAN ALPHEN (1988)). A significant density-driven cross-shore circulation can be correlated with horizontal density gradients, corresponding to high discharge events of the river Rhine (HOEKSTRA & STOLK (1992)). Most important for the coastal morphology is the highly variable wave climate resulting from winds generated in the North Sea (moderate height ca. 1 m and short period of 5 s). The highest waves are from the north-west because of the longer fetches in this sector (VAN RIJN (1997)). Generally, the sandy barrier system is fronted by a beach and surf zone containing 2 to 3 breaker bars. The inner bar is usually attached to the beach as a ridge-and-runnel cut by drains and rips, whilst the second and third bars are highly rhythmic (SHORT (1992)). Although structural impacts are widespread, natural beach processes dominate the entire coast with a hierarchical bar morphology related to cross-shore wave breaking. The Delta area (Zeeland) is a complex of large estuaries and tidal basins, seaward of which ebb-tidal delta's determine the morphology of the shallow North Sea (VAN ALPHEN & DAMOISEAUX (1989)). Along the Holland coast large sand ridges are present in the lower and middle shoreface. The sediment distribution in the shoreface-connected ridges indicates that they are migrating in the direction of the dominant flood current, seaward and northeastward along the coast at an estimated rate of 0.5-1 m per year (VAN DE MEENE (1994)). The northern part of the Holland coast is strongly influenced by the large tidal inlet of the Marsdiep, the southernmost inlet of the Wadden Sea.

1.4. Research objectives and outline

Studying sediment- and morphodynamics of a siliciclastic coastal system requires knowledge on its physical functioning in space and time. Such a holistic approach implies that a wide range of components have to be examined in detail which can not be realised by a single investigation. In the framework of this research, it was preferred to study the sedimentary environment as a whole, but concentrating on the most dynamical areas. The above-mentioned characteristics of the Belgian coastal zone and the comparison made with adjacent coastal areas put forward a number of research questions:

- impact of nearshore morphology on coastal behaviour ?
- role of sand banks controlling sediment transport processes ?
- does a morphological system exist with continuous interactions between water movement, sand transport and morphology (process-response system) ?
- cross-shore sediment exchange versus well-defined transport pathways ?
- sensibility – vulnerability of the coastal system ?

Given the global research questions, a detailed investigation is carried out in the western Belgian Coastal Zone, extending about 9 km offshore. Research activities are mainly focused on the impact of well-developed sand bodies on actual sediment transport processes. To study causal relationships in coastal erosion and accretion phenomena, sediment fluxes are investigated in an area between the Coastal Banks and the more offshore Flemish Banks and towards the beach itself.

To fully comprehend ongoing sediment transport processes an integrated research strategy was set up, involving sedimentological and geo-acoustical methodologies enabling to reveal changes in the sedimentary pattern on a 'short-', 'medium-' and 'long-term' basis (according to the response time needed to adjust to changes in the hydraulic regime) (Fig. 1.02). Moreover, it was felt necessary to consider the Coastal Banks as part of a larger sediment transport system as the coastal area is characterised by the presence of pronounced ebb and flood dominated zones.

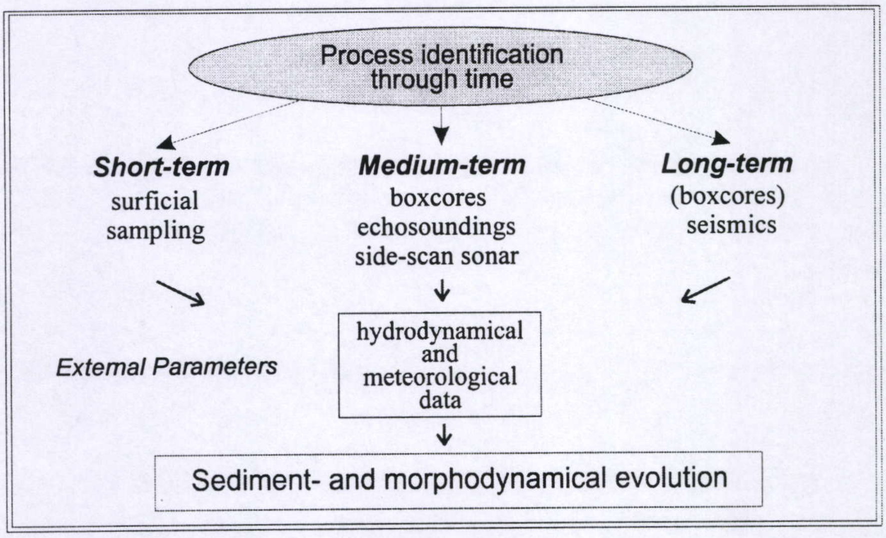

Figure 1.02 - Flowchart illustrating the objective and the methodologies used.

In the perspective of such a sediment and morphodynamical study in space and time the following scientific aims can be put forward:

- a geological and sedimentary inventory;
- investigating the processes governing their existence;
- situating them in space and different time scales;
- identifying likely sources, sinks and transport corridors;
- determining causal mechanisms.

In the framework of this study, these goals were attempted through a monitoring of the coastal system. Chronosequential measurements enabled to study sedimentary fluxes under a variety of circumstances. This led to an evaluation of the differentiation in processes as well spatially as temporally, and aided in the determination of causal relationships.

2. AREA UNDER INVESTIGATION

2.1. Hydrography

The morphology of the near coastal area between Nieuwpoort and Oostende can best be described using the bathymetric chart compiled by EUROSENSE on the basis of echosounding data from the *Belgian Waterways Coast Division** and contoured at a 1 m interval (HOUTHUYS & VAN SIELEGHEM (1993)) (Fig. 2.01). The near coastal Baland Bank, the Westdiep swale, the southern part of the Middelkerke Bank and the Ravelingen sandbank were subject of a detailed investigation. From this chapter on, all depths are indicated according to the Mean Lowest Low Water at Spring (MLLWS), being the hydrographic reduction level for Belgium and The Netherlands.

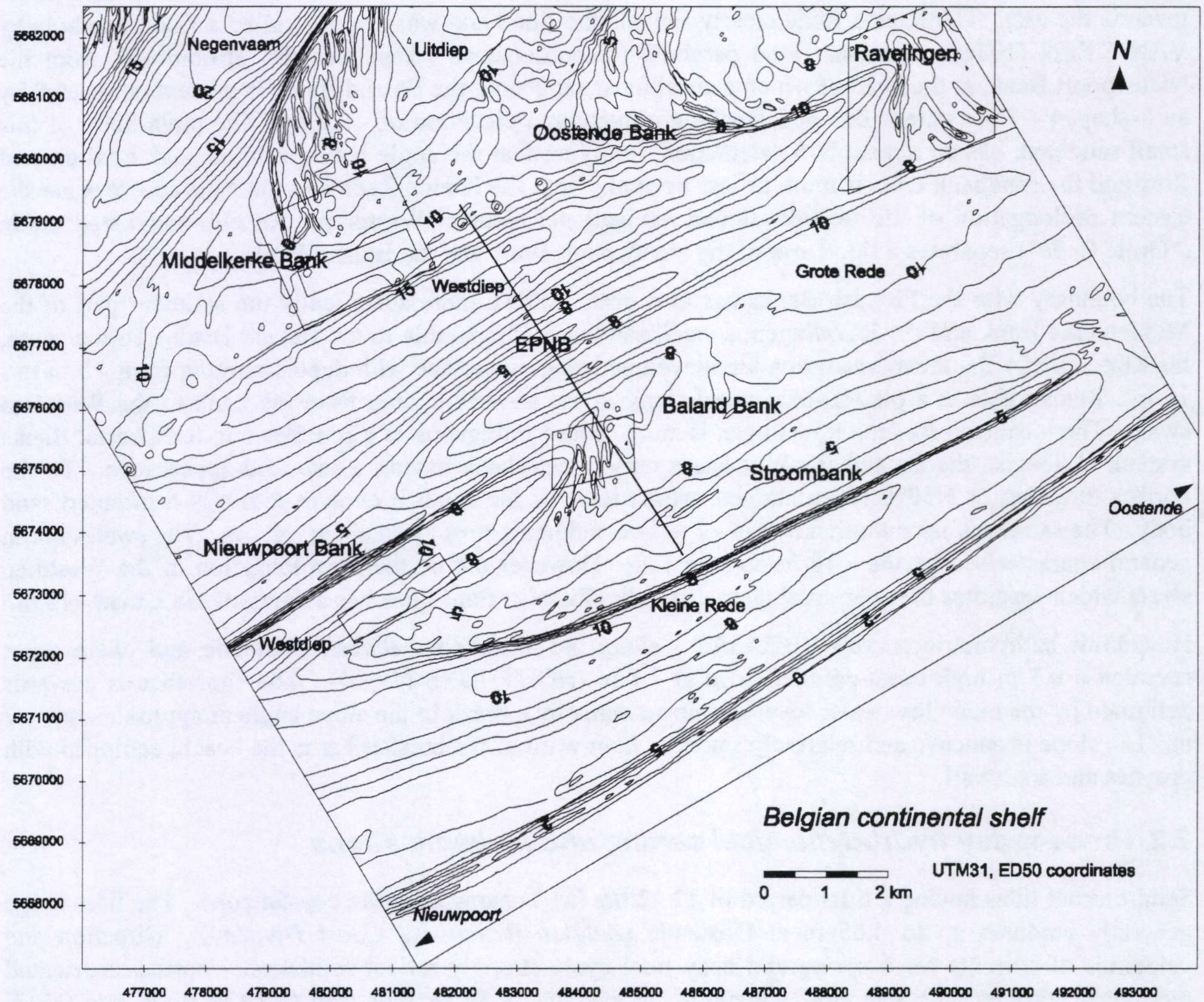

Figure 2.01 – Bathymetry of the area under investigation (HOUTHUYS & VAN SIELEGHEM (1993)). The frames delineate the areas used for the volume computations (Chapter 6). (EPNB: Eastern prolongation of the Nieuwpoort Bank). The line corresponds to the localisation of the seismic profile in Figure 2.07.

**Belgian Waterways Coast Division, abbreviated referred to as AWK (Afdeling Waterwegen Kust)*

The main morphological units in the near coastal area are the Nieuwpoort Bank and the Stroombank, respectively 11 km and 12.5 km long and contoured by the - 5 m line. Their height varies around 7 m in respect to the adjacent swales; their spacing approximates 2.3 km. In comparison to the coastline, they have a clockwise deviation of respectively 3.5° and 7.5°. Both sandbanks are strongly asymmetric and have their steepest slope in a landward direction. The Nieuwpoort Bank has a steep slope varying from 1° to 1.45°, whilst for the Stroombank 0.6° to 1.8° is reached (DE MAEYER & WARTEL (1988)). The gentle seaward flank has an average inclination of 0.25° and is often composed of two rectilinear segments, the upper being steeper than the lower. The crest is a narrow zone between the landward and seaward flank, which can reach up to - 2.5 m. In respect to the maximum tidal current velocities, the Stroombank has a clockwise offset of 10° against 4° for the Nieuwpoort Bank. On an old navigational chart (STESSELS (1866)) the Stroombank was still connected to the shoreface, but with the increasing activity of the harbour of Oostende the eastern end of the bank is continuously dredged (navigation channel maintained at - 8 m). Still the adjacent swale ("Kleine Rede") becomes more and more shallow towards the east. The Kleine Rede clearly funnels the flood and was already called a flood parabola by VAN VEEN (1936). Another flood parabola ("Noordoostpas") separates the Stroombank from the Nieuwpoort Bank, at the head of which a curvilinear sandbank, the Baland Bank, is present delineated by an S-shaped - 7 m contour line and reaching a maximum elevation of - 3.2 m. The main body of this small sandbank has an almost N-S orientation, implying that the angle between local peak tidal current flow and the sandbank crest is more or less normal. Both the Kleine Rede and the Noordoostpas are the eastern prolongation of the well-developed navigational channel Westdiep. An ebb-dominated swale ("Grote Rede") separates a flood arm of the Nieuwpoort Bank and the Baland Bank.

The boundary with the Flemish Banks has also been studied, more specifically the southern part of the Middelkerke Bank and the Ravelingen, a small sandbank comparable to the Baland Bank. To the south, the Middelkerke Bank evolves into a less developed sloping surface with depths ranging from - 5 m to - 10 m. Remarkable is a plateau-like morphology in the transition zone from the bank to the Westdiep swale. The localisation of the Ravelingen is more or less ambiguous as it intrudes into the Coastal Banks system. Likewise the Baland Bank, it has a curvilinear shape having a two-fold appearance. To the north a direction of N30°E is maintained, whilst towards the south it evolves into a N-S oriented sand body. The sandbank is contoured by the - 7 m line and has a crest up to about - 4.1 m. The swales are in general characterised by the - 10 m contour line. However the northern prolongation of the Westdiep swale which separates the near coastal area from the Flemish Banks reaches a depth of more than - 15 m.

Hovercraft bathymetric surveys (BEASAC*) along the nearshore between Oostende and Nieuwpoort revealed a 0.5 m high coast-parallel ridge at - 1 m (HOUTHUYS (1996)). The shoreface is upwards delimited by the mean low water level and downwards by a break in the slope angle at approximately - 7 m. The slope is concave and relatively smooth. Landward of the breaker bar is the beach, equipped with groynes and a seawall.

2.2. Present-day hydrodynamical setting and its implications

Semi-diurnal tides having a tidal period of 12.42 hrs (M_2) characterise the coastal zone. The tidal range generally amounts up to 4.65 m at Oostende (*Belgian Waterways Coast Division*). Direction and velocities of currents for a spring and neap tidal cycle strongly reflect southwest - northeast oriented rectilinear currents with ebb peak velocities, on average 39 % smaller than those at flood tide (VAN CAUWENBERGHE (1992)) (Fig. 2.02) and characterised by a large neap-to-spring variation. HUNTLEY & MACDONALD (1996) modelled the alongshore tidal flow due to the tidal wave propagation from west to east along the Belgian coast. They concluded that the elevation and current are in phase and the tide is just an eastwards-propagating progressive wave. The tidal wave becomes more like a standing wave with decreasing depth towards the shore, with maximum tidal flows occurring earlier inshore than offshore. This explanation is consistent with the approximate phase lag of 1.5 hrs between tidal elevation and current speed observed off the Belgian coast (VAN CAUWENBERGHE (1992)). Maximum erosion potential due to current velocities up to 1.18 m/s is reached around high

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* BEASAC®, *Belfotop Eurosense Acoustic Sounding Air Cushion platform*

water. Sedimentation mainly occurs at slack water, three hours before and after maximum elevation at spring tide or up to four hours during neap tide. The wave climate along the Belgian coast is typical of short-fetched seas showing a significant wave height between 0.50 and 1 m with a mean period of 3.5 - 4.5 s. Predominant winds blow from the SW, the most effective storm direction being from the NW (MINISTERIE VAN DE VLAAMSE GEMEENSCHAP (1993)). These hydrodynamical characteristics exert a marked influence on the nature and distribution of sediments.

Most peculiar is the presence of a mud plume extending from the river Westerschelde up to Oostende. Although the origin of the suspensive sediments is not clear, it is generally accepted that this fine fraction is dynamically trapped by a convergence of residual flood and ebb currents enhanced by a strongly coastwards orbital wave motion (i.e. VAN VEEN (1936), BASTIN (1974), NIHOUL & GULLENTOPS (1976)). The spatial and temporal variability of wash load in the Belgian Coastal Zone has been illustrated in the introductory chapter. In the following paragraph emphasis is put on a smaller mud plume associated with the river IJzer near Nieuwpoort. The same structure can however be found around the harbour of Oostende.

The outflow of the river IJzer near Nieuwpoort can easily be followed using calibrated digital multispectral airborne scanner registrations (Section 1.2) (FRANSAER (1994)). During most of the high water phase hardly any influence of the river can be noted. From the beginning of the ebbing tide a sediment plume can be distinguished associated to the river outlet. The spatial structure of the plume is twofold. At the end of the flood, water is dumped outside the harbour of Nieuwpoort; since the current is still in a northeastern direction suspension load is advected for a few kilometers until it gradually spreads out. Shortly afterwards, a part of the plume settles out until the ebbing phase reaches its maximum leading to a sediment plume towards the south-west. Sediment concentrations remain high due to high current velocities. The older sediment plume with less suspension subsequently encapsulates the younger highly concentrated plume with a westward displacement of about 2 km offshore. In general, the sediment plumes are spread out up to 3 to 5 km westward of the harbours at ebb tide. At the end of the ebbing phase the current has a coastward direction meaning that remnants of such muddy plumes can reach the adjacent beaches. In the case of the river IJzer, the beach of Oostduinkerke is clearly influenced by this phenomenon and the groyne of Lombardsijde seems to act as a steering agent for the creation of local turbidity maxima at the nearby beach.

2.3. Physical characterisation of the beaches adjacent to the study area

The beaches are of a sandy macro-tidal ridge-and-runnel type and are well developed in the non-defended areas. From Oostduinkerke to Mariakerke the morphology of the beaches gradually changes from a well-developed ridge-and-runnel type to a gently sloping, rather smooth beach type. West of Nieuwpoort, most of the beaches are devoid of hard defence structures giving rise to up to five well-defined ridges, which are exposed at low tide. The intertidal zone varies between 500 m and 250 m in width. The overall beach slope is about 1-2 %. Most of the time the beaches are dissipative (MASSELINK & SHORT (1993)). Bedforms related to the combined action of currents and waves are present, increasing in importance towards the west.

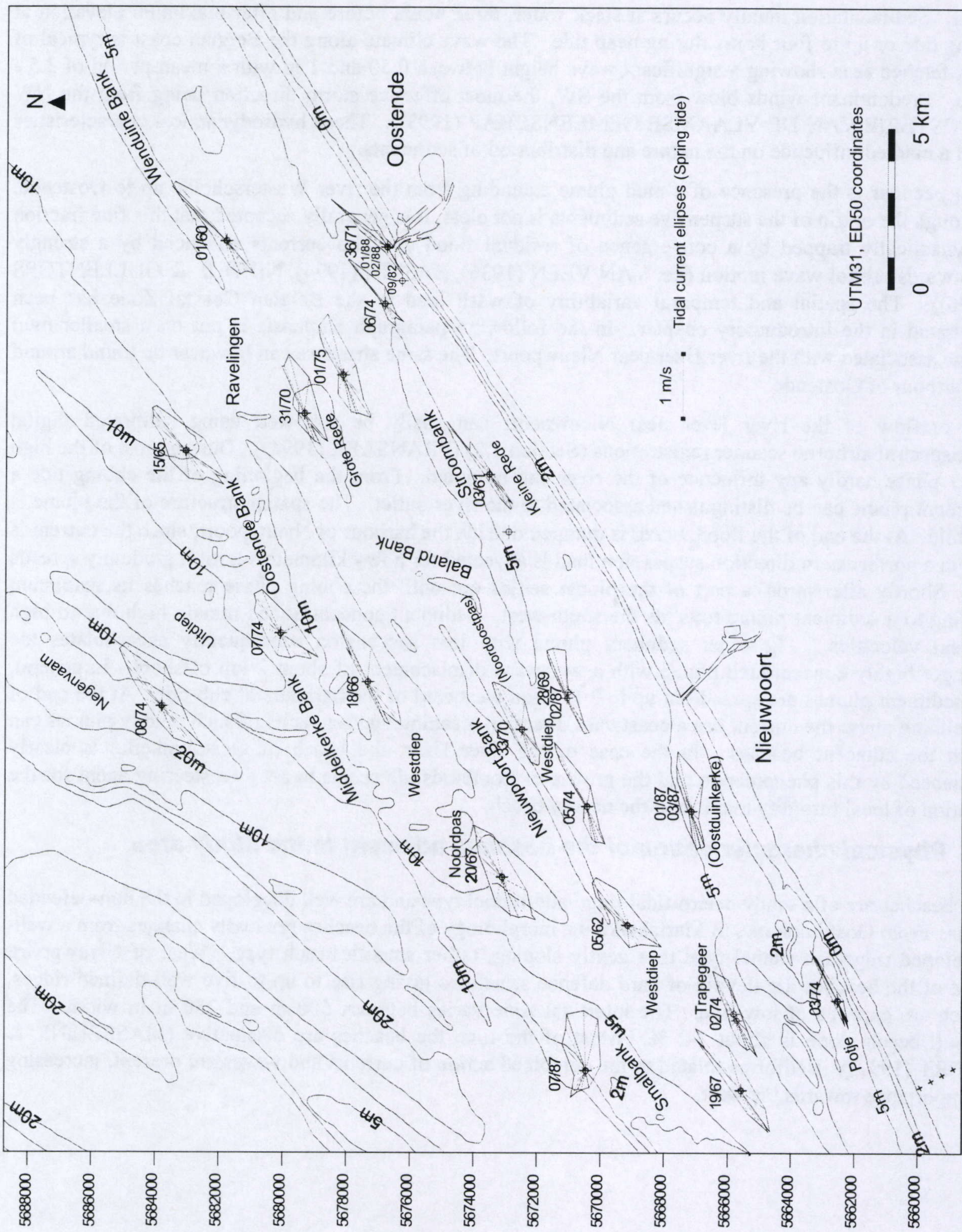


Figure 2.02 - Overview of the study area with localisation of tidal current ellipses from moored instruments (VAN CAUWENBERGHE (1992)). The current meters were generally deployed at 3 m above the seafloor.

Surficial sediments are in general well sorted and fine to medium grained. The mean grain size along the low-tidal zone between Oostduinkerke and Mariakerke varies between 210 µm and 277 µm. Cross-shore grain-size differences amount approximately 20-40 µm, the coarsest sediments being deposited at the high tidal zone (ELLIOTT et al. (1997)). However, hardly any beach is free from human interference meaning that cross-shore differentiation may not be significant. Muddy sediments can be frequently observed on the beaches nearby the harbour of Nieuwpoort. These washload deposits can be correlated with remnants of muddy plumes associated with the harbour of Nieuwpoort, as described in the previous paragraph. VAN CRAENENBROECK (1985) also distinguishes greenish mud of biological origin, brownish mud deposited under a low current regime of a turbulent flow and brownish to greyish mud possibly settled out of heavy suspensions. The muddy deposits intercalate with the sandy sediments leading to flaser bedding.

On the basis of beach profiling during the period 1982-1987, DE MOOR (1988) presents a general scheme of residual erosion and residual accretion along the Belgian coast. According to DE MOOR (1979, 1993), the alternating state of the beaches being as well erosional as accretional in a period of 50-70 years, implies a cyclicity of natural origin. Whether these long-term changes are controlled by the slow passage of so-called "sandwaves" (VERHAGEN (1989)) or related to changes in wave energy commanded by edge waves or changes in offshore topography is still a matter of debate (DE MOOR (1993)). The 18.6 yr nodal cycle can also have its impact on tidal sedimentation (OOST et al. (1993)). Seasonal changes can be significant (DE MOOR (1988)).

DE WOLF et al. (1993) discuss the morphological trends of beach and foreshore out of remote sensing based surveying in the period 1983-1992 (Fig. 2.03). The well-developed beaches west of Nieuwpoort are merely accretional, whereas the section between Westende and Oostende is generally suffering from mild erosion. The area west of Nieuwpoort has also a shallow foreshore and shoreface, whilst to the east the navigational channel "Kleine Rede" approaches the coast; hence a funnelling of the current may be expected. East of the harbour of Nieuwpoort, there is clearly a sediment deficit as the longshore sediment transport is hampered by the harbour constructions. Remark the persistent erosion west of De Panne, which is possibly related to the heavy erosion east of Dunkerque (Section 1.3). The construction of a long seawall as reinforcement of the dune foot was not able to withstand the heavy storms of February 1990. Between De Panne and Koksijde the beach and foreshore may be locally eroded due to the nearby pronounced flood dominated swale "Het Potje" (MINISTERIE VAN DE VLAAMSE GEMEENSCHAP (1993)). Moreover, differential movements of breaker banks may also cause localised erosion.

Recent reports (MIWE 94.001) of the Belgian Waterways Coast Division confirm the above mentioned conclusions. Indeed, only minor volume changes of the sand budget have been reported. Moreover, areal changes seem to be more apparant. Also mentioned is a fairly stable foreshore around Westende-Bad, except for some localised erosion caused by groynes. Middelkerke-Bad is regularly replenished with coarser offshore sands, but as stated in the reports this is merely to prevent erosion. From Raversijde to Oostende the foreshore is relatively stable.

In the framework of the MASTII - CSTAB project (O'CONNOR (1996)), detailed field experiments were carried out at Groenendijk Bad, west of Nieuwpoort (Fig. 1.01, 2.03). The experimental site was chosen outside the influence of any hard defence structures to gain insight into the natural processes governing a typical ridge-and-runnel-like beach morphology. Tide and wave-induced pressure, time-series of flow velocities and suspended sediment concentrations were measured at four locations in the high- and mid-tidal zones. Moreover, as well magnetic as fluorescent tracer experiments were carried out in combination with topographic measurements of the beach morphology.

Interesting to the present study, is the detailed investigation of the incident wave climate. This showed that waves seemed to be flattened during the flood, meaning that currents work with wind-driven waves that are incident at a small angle to the shore. During the ebb however, tidal currents are weaker, hence the waves are steeper and break sooner (VOULGARIS & SIMMONDS (1996)). Sediment transport modelling showed that suspended load accounted for more than 80 % of the total sediment transport rate.

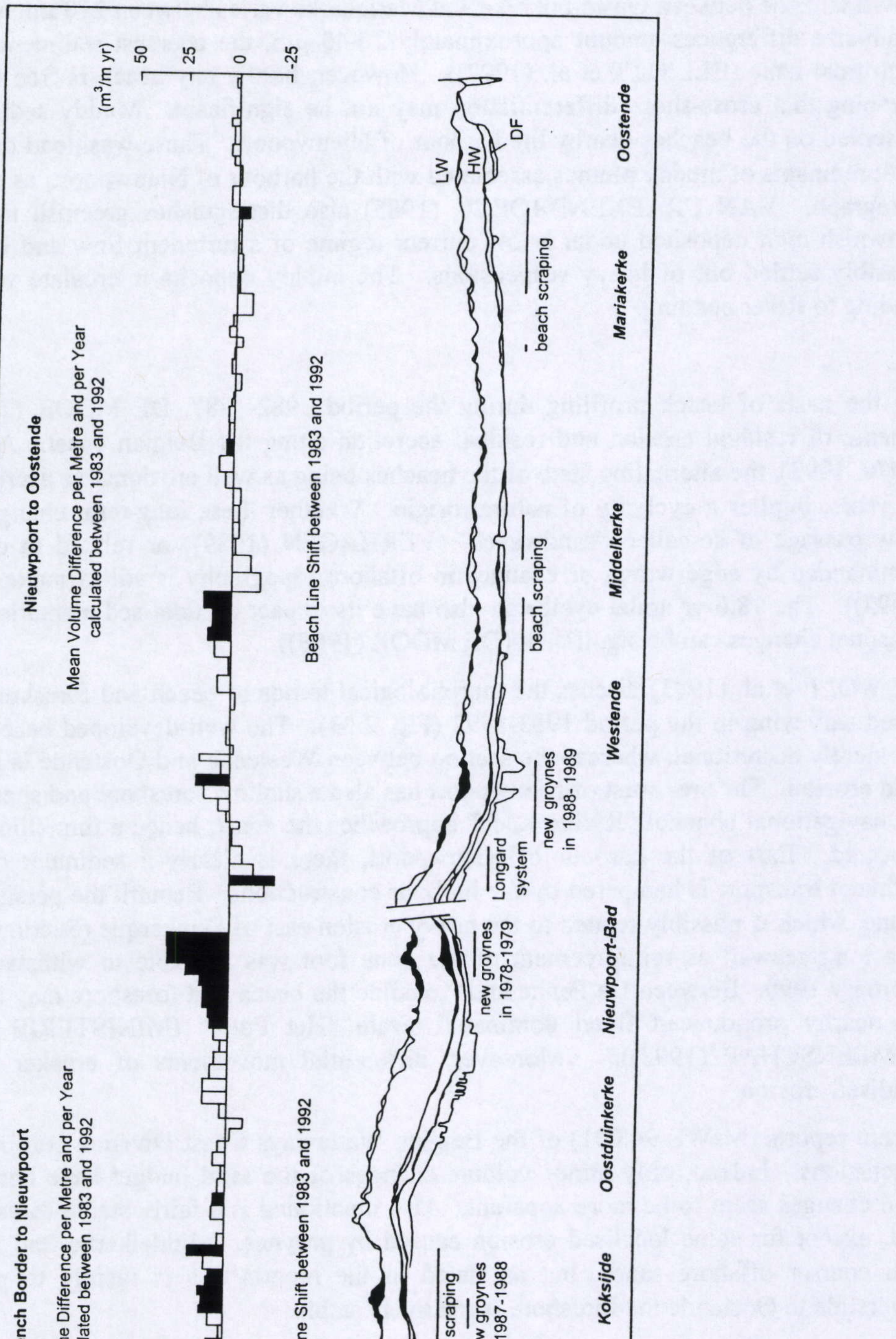


Figure 2.03 - Mean volume differences per metre and per year along the coastal stretch De Panne-Oostende (DE WOLF et al. (1993)).

2.4. Geological framework

2.4.1. Introduction

The Belgian Basin can be considered a bight-like extension of the southern North Sea Basin and is entirely situated on top of the London-Brabant Massif. This relatively stable continental block of Palaeozoic age was only flooded since Late Cretaceous times. The Cenozoic stratigraphic record is almost completely dominated by marine to marginal marine deposits. A shallow shelf environment persisted throughout the Palaeogene and the area was periodically flooded during periods of high relative sea-level (DE BATIST & HENRIET (1995)). A gradual infilling of the basin was provoked by a constant sediment supply of southern origin, controlled by a mainly deltaic depositional system. Sedimentation is driven by a proto Rhine-Meuse-Scheldt fluvial drainage system caused by the Alpine uplift of the hinterland (JACOBS & SEVENS (1993)). During the Neogene, the depocentre shifted north of the area into the main North Sea Basin. In Quaternary times, the area emerged repetitively in response to glacio-eustatic sea level falls. The Quaternary cover is relatively thin and mainly consists of Holocene tidal sandbanks, locally overlying Pleistocene deposits. A transgressive coastal development resulted in the present-day closed coastal barrier (BAETEMAN & DENYS (1997)).

2.4.2. Tertiary development

Recently, the Tertiary substratum, its stratigraphy and structural setting have mainly been studied by BASTIN (1974), DE BATIST (1989), HENRIET & DE MOOR (1989), DE BATIST & HENRIET (1995) and JACOBS & DE BATIST (1996). Palaeomorphological investigations were carried out by MOSTAERT et al. (1989), LIU et al. (1992; 1993), whilst the work of JACOBS et al. (1990), JACOBS & SEVENS (1993) and JACOBS & DE BATIST (1996) was merely confined to the lithostratigraphy of the offshore Tertiary. JACOBS et al. (in press) present a review of all available data on the Tertiary of the coastal plain and some parts of the offshore area.

Figure 2.04 shows the subcrop pattern of the Palaeogene seismic stratigraphic units in combination with the onshore lithostratigraphic units (DE BATIST & HENRIET (1995)). The Palaeogene strata exhibit a general strike of 135°-140° NE and a dip of 0.5°-1° NE. The subcrop area of the present investigation lies completely within the Ypresian. In the nearshore areas, detailed information is not available due to the presence of shallow gas. The seismic facies of the Ypresian suggests a relatively long period of stable, low-energy conditions. Onshore, it is interpreted as a mud-shelf environment (JACOBS & SEVENS (1993)).

The morphology of the top-Tertiary erosion surface was investigated by LIU et al. (1992). On the basis of high-resolution reflection seismic data, he concluded that the morphology was only slightly controlled by the lithology and structure of the underlying Tertiary strata. Remarkable planation surfaces, palaeovalleys and other morphological features have been identified. From Figure 2.05 it can be seen that off the Belgian Coast, the erosion surface first rises to a marginal platform and then slowly slopes down in seaward direction through a series of a few well-defined planar elements that are incised by two major palaeovalleys. These palaeovalleys seem to form the link between the drainage systems of the Flemish Valley and the Coastal Valley, known from onshore studies. Towards the west, the Coastal Valley extends into the Western Valley, scoured into the Ypresian clay. The NW-trending Oostende Valley runs more or less parallel to the strike of the underlying Ypresian clay. The valley is quite narrow near Oostende and widens towards the sea where it becomes shallow and flat-bottomed. There is a distinct disconformity and stratigraphic break between the Palaeogene and Late-Pleistocene to Holocene sediments (DE BATIST & HENRIET (1995)).

The scouring of the Ypresian clayey sediments, west of Nieuwpoort, is considered a source for the muddy deposits found along the Belgian continental shelf (VAN VEEN (1936); BASTIN (1974)). Authors as VAN MIERLO (1899) and VAN VEEN (1936) also retained the idea that the mud could also be formed out of fine detritus of the English and French coast; however, VAN VEEN was more in favour of autochtonous clay layers being eroded.

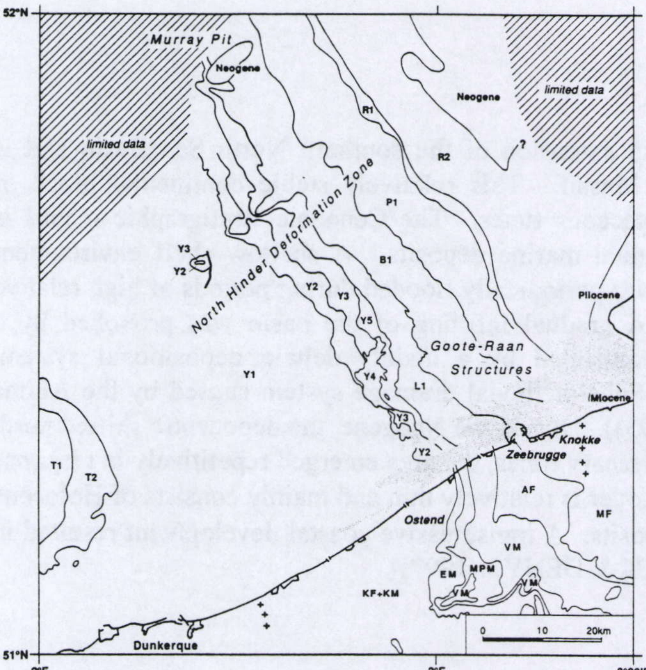


Figure 2.04 - Simplified map showing the subcrop pattern of the Palaeogene seismic stratigraphic units (offshore) and lithostratigraphic units (onshore) beneath the Quaternary cover, and the location of the main structures. KF, Kortrijk Formation; KM, Kortemark Member; EM, Egem Member; MPM, Merelbeke and Pittem Member; VM, Vlierzele Member; AF, Aalter Formation; MF, Maldegem Formation (DE BATIST & HENRIET (1995)).

BASTIN (1974) argued that especially in areas where Quaternary sand has been eroded by strong tidal currents, the underlying Tertiary clay is being decompressed. Due to its heterogeneous fabric the clay will form chips, that are carried by the currents as clay pebbles transportable over a large area. This process can give rise to an enormous amount of fine-grained sediments. This is likely the case along the west coast. The Ypresian clay shows an upwelling in the Westdiep swale likely related to a result of decompaction. Caution should be taken in dredging areas where those clay layers are being eroded.

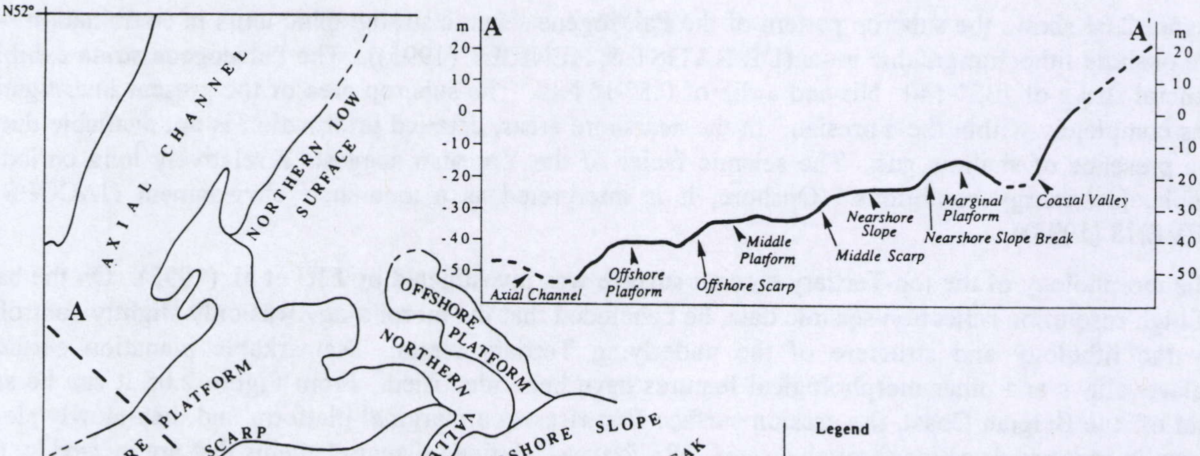


Figure 2.05 - The main morphological units of the top-Tertiary erosion surface (LIU et al. (1992)).

2.4.3. Quaternary development

The western part of the Holocene Belgian coastal plain has recently been studied by e.g. BAETEMAN (1981; 1993), BAETEMAN & VAN STRIJDONCK (1989) and BAETEMAN & DENYS (1997). DE MAEYER et al. (1985) and WARTEL (1989) studied the Quaternary sediments and depositional environment of some of the Coastal Banks, whereas DE BATIST et al. (1993), TRENTESAUX (1993), BERNE et al. (1994) and STOLK (1996) concentrated on the formation of the Middelkerke Bank within the MAST projects RESECUSED and STARFISH (DE MOOR & LANCKNEUS (1993); HEYSE & DE MOOR (1996)). An overview of the Holocene evolution of the Belgian coastal plain is given in MARECHAL (1992) and HOUTHUYS et al. (1993).

MOSTAERT & DE MOOR (1989), KÖHN (1989) and DENYS & BAETEMAN (1995) published Holocene sea-level curves for Belgium. LOUWYE & DECLERCQ (1998) specifically discuss the variations during the last 2500 years. Figure 2.06A gives an indication of the chronology of inundation phases during the Holocene (LOUWYE & DECLERCQ (1998)). Figure 2.06B represents an age-depth reconstruction of the relative sea-level rise in Belgium. The results are particularly based on basal peat data, assessed in terms of local water and tide levels (DENYS & BAETEMAN (1995)).

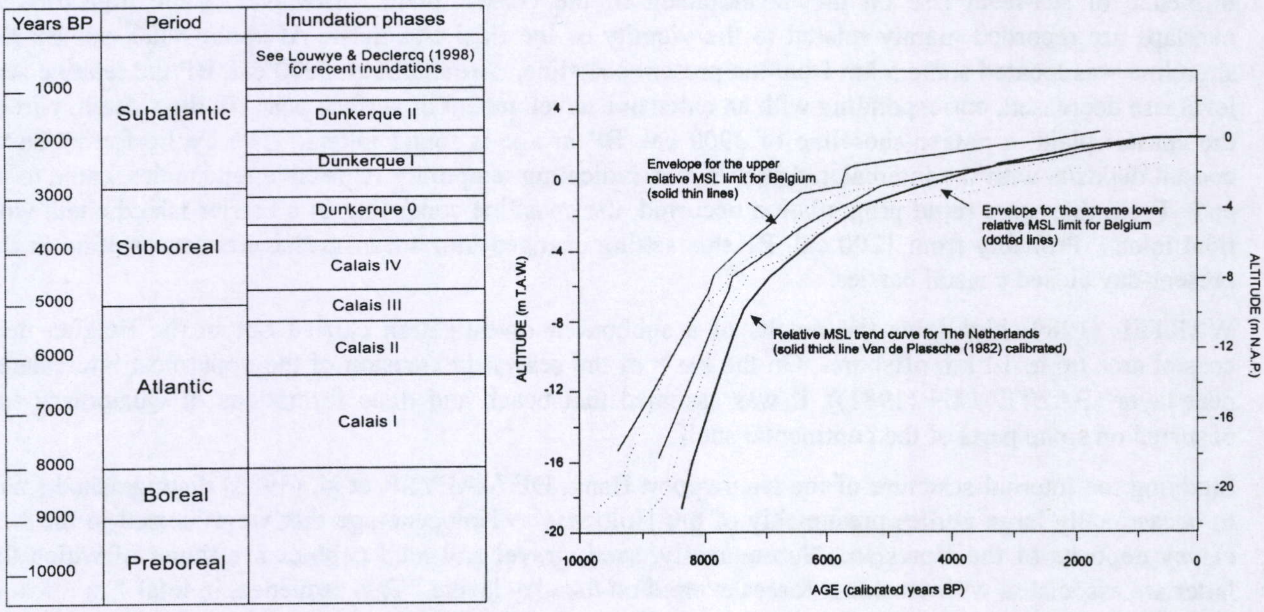


Figure 2.06 - A. Chronology of the inundation phases during the Holocene (In: LOUWYE & DECLERCQ (1998); modified after BAETEMAN (1978); ZAGWIJN & VAN STAALDUINEN (1975) and MOSTAERT (1985)); B. Holocene sea-level curve (DENYS & BAETEMAN (1995)).

During the Holocene, the coastal plain was subjected to marine, freshwater and terrestrial conditions giving rise to a stratigraphic record of sediments (sand, silt and clay) of maximum 30 m in thickness and mainly reflecting tidal flat conditions. Towards the seaward part of the coastal plain, only marine and brackish clastic sediments have been deposited that are in some places overlying a basal peat layer (BAETEMAN & VAN STRIJDONCK (1989)). This organic rich layer at the base of this marine Holocene sequence as well as the interfingering complex of peat layers are dated, enabling to establish a geochronology linking the lithological classification (BAETEMAN & VAN STRIJDONCK (1989)). In general, the basal peat and also the intercalated peat layers are lacking in the very seaward area, where also the Pleistocene deposits are almost completely eroded (BAETEMAN & DENYS (1997)).

The Holocene development of the Belgian coastal plain is characterised by a rapid infilling following the rate of sea-level rise and the morphology of the Pleistocene substratum (BAETEMAN & DENYS (1997)). During the early Holocene (before 7800 cal. BP), a mean rate of sea-level rise of about 7m/1000yr provided a high sediment supply and resulted in a relatively energetic depositional environment. A tidal flat, more particularly sandflats and associated tidal gullies started to develop, characterised by a continuous deposition of clastic sediments (BAETEMAN & VAN STRIJDONCK (1989)). Changing conditions in the most silted-up parts of the former Pleistocene valleys induced local peat growth on the tidal flat sediments, whereas in the rest of the plain mudflats and salt marshes developed. After a distinct retardation of the relative sea-level rise around 7500-7000 cal. BP, tidal sedimentation within the plain decreased progressively from +/- 7300 cal. BP onwards in favour of peat development. In view of the rather continuous chronology of the different peat layers, it seems likely that the spatial and temporal distribution was to a substantial extent determined by the configuration of the tidal flat and the lateral development of its subenvironments. This statement implies that no (supra)regional changes are necessary to explain the lithostratigraphy of the coastal plain, and that consequently the division of the Holocene sequence into 6 Dunkerque and 5 Calais deposits as outlined in HOUTHUYS et al. (1993) can not be sustained.

The extension of the coastal plain was close to its present limits by 6500 BP, indicating a reduction of the influence of sea-level rise on the development of the coastal plain. However, some transgressive overlaps are recorded mainly related to the vicinity of the tidal channels. At about 6000 cal. BP the shoreline was located some 5 km from the present coastline. Around 5500-5000 cal. BP the relative sea-level rise decreased, corresponding with an extensive development of surface peat. In the western part of the coastal plain, a palaeo-shoreline of 3900 cal. BP in age is found inland. The cyclic formation of coastal deposits with the intercalated peat layers, indicating temporary regressive tendencies, came to an end. From then on a rapid progradation occurred, the coastline consisting of a barrier island chain with tidal inlets. Probably from 1200 cal. BP this setting changed into a transgressive coast resulting in the present-day closed coastal barrier.

WARTEL (1989) highlights the results of a subbottom investigation carried out in the Belgian near coastal area up to 14 km offshore. On the basis of the seaward extension of the uppermost intercalated peat layer (BAETEMAN (1981)), it was assumed that beach and dune formations of Quaternary age occurred on some parts of the continental shelf.

Studying the internal structure of the Nieuwpoort Bank, DE MAEYER et al. (1985) distinguished small to occasionally large gullies presumably of pre-Holocene to Holocene age that were incised in the stiff clayey deposits of the Ypresian. Subsequently, sand, gravel and mud pebbles are found of which the latter are associated with erosional forces exerted on the clay layers. This sequence, in total 1 m thick, is overlain by a 60 cm thick shell layer comparable to the *Angulus Pygmaeus* association found in the Zeeland Banks (LABAN & SCHÜTTENHELM (1981)). The occurrence of gravel and the random orientation of the shells indicate a highly energetic environment, presumably nearshore or beach. Moreover, the characteristics of the overlying sediments being composed of alternating sand and clay beds or laminae sometimes in combination with concave upwards oriented shells, suggest deposition in an intertidal environment. The occurrence of several relatively small gullies confirms this hypothesis.

The succession of horizons can be recognised in most of the subbottom profiles, ran transversally over the near coastal area. Figure 2.07 shows a seismic profile extending from the southern part of the Middelkerke Bank over the Baland Bank towards the Stroombank.

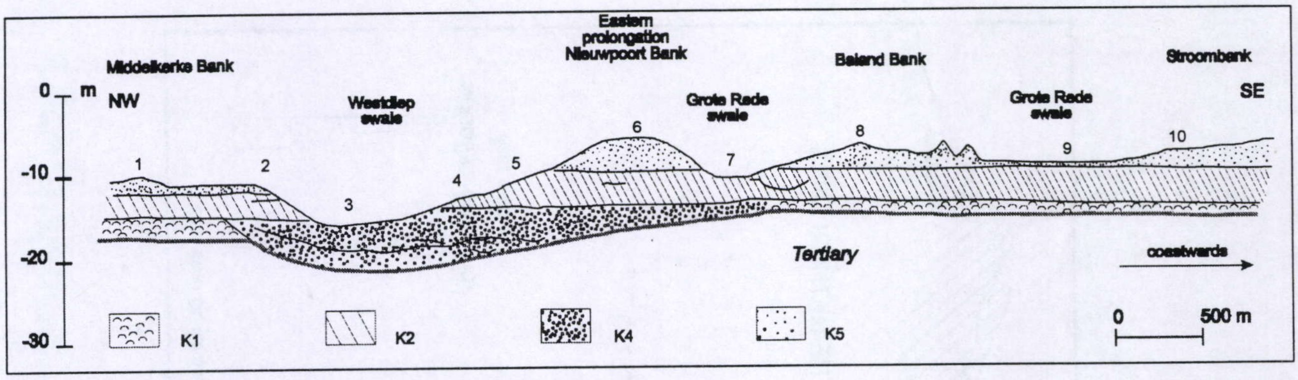


Figure 2.07 - Seismic profile comprising the southern part of the Middelkerke Bank, the Baland Bank and the Stroombank (modified after WARTEL (1989)) (Localisation, see Figure 2.01). The numbers refer to boxcore locations taken within the present investigation (Fig. 6.32).

Similar to the Nieuwpoort Bank area, small gullies can be observed in the uppermost horizon K2, whilst no gullies are found in the lowermost horizon (K1). A correlation between both locations remains uncertain; however, it confirms the tidal nature of the environment. The larger gullies are recognisable on adjacent profiles, so that their areal distribution could be mapped. Correlation was possible with an important inland tidal gully observed by BAETEMAN (1981; 1985). The tidal flat deposits (K2) are overlain by larger sediment bodies which lack however any stratification. Grain-size analysis of a core sampled in a sediment body north of the Nieuwpoort Bank reveals a relatively uniform grain-size distribution, mainly composed of fine sands comparable to the present day situation. The uppermost layer represents active marine deposits.

According to BALSON et al. (1991), the mainly fine-grained, locally silty and laminated sand builds up Holocene outer tidal deltas, locally resting on Early-Holocene tidal deposits. Especially in the Dutch coastal waters, the total thickness of the tidal deposits can attain more than 30 m.

2.4.4. Historical evolution

LIGTENDAG (1990) reconstructed the Belgian-Dutch coastline in the period 1600-1750. On the basis of a detailed historical-geographical investigation he concluded that the Belgian coastline was fairly stable up till 1750, whereas afterwards the high water line was subjected to various displacements. Between the French border and Nieuwpoort, the high water line shifted 100 – 300 m in a seaward direction, whilst between Nieuwpoort and Wenduine a 100 m displacement in a landward direction was determined (Fig. 2.08).

A hydrographic analysis of the Flemish Banks in the period 1800-1968 showed a relative stability of the major depth lines of - 8 m, - 10 m and - 20 m (VAN CAUWENBERGHE (1971)). Shallower areas are more subject to changes, partially due to their complex shapes that are moreover difficult to measure accurately. Taking into account a significant error range for the older charts and supported by the findings of BASTIN (1964), VAN CAUWENBERGHE concluded that the Flemish Banks are in some kind of dynamic equilibrium whereby even storms and strong intermittently currents are not capable to induce a significant transport of sediments in between the banks, leading to a quasi-permanent availability of sand for the up-building of the banks.

Noteworthy are the Ravelingen and the Baland Bank (Fig. 2.01) that were first drawn up on the charts of 1924-1929, both characterised by a minimum depth of about - 4 m and interpreted as being part of the neighbouring major sandbanks (VAN CAUWENBERGHE (1971)). It is not clear whether their existence is related to the dredging activities of the eastern part of the Stroombank which permitted a direct access to the port of Oostende around 1901-1903.

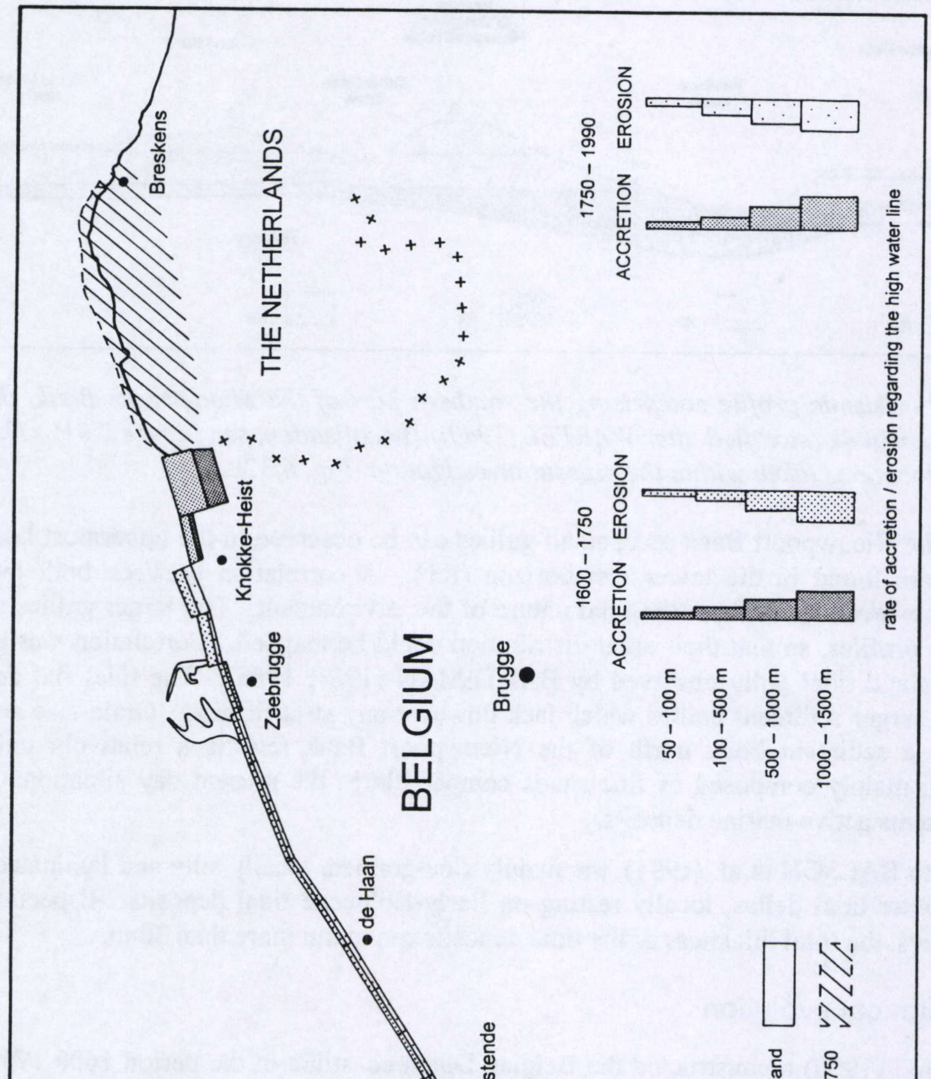


Figure 2.08 – Historical evolution of a part of the Belgian – Dutch coast in the period 1600 – 1750 and 1750 to present (modified after LIGTENDAG (1990).

Also the swales of the major sand bodies seemed to be rather stable since the period 1924-1929. The near coastal Westdiep swale and the Noordpas (Fig. 2.01) remained more or less in position, respectively since 1879-1882 and 1901-1903. VAN CAUWENBERGHE (1971) also mentions S-shaped movements of the Nieuwpoort Bank and Stroombank (Fig. 2.01) in the order of 300 to 350 m before 1879. These findings could support the hypothesis of CASTON (1972), and will be discussed in Chapter 6.

Related to the study area, major changes can be determined for the Grote Rede and Kleine Rede (Fig. 2.01). Referring to the hydrographic chart of STESSELS (1866) (Fig. 2.09), it is clear that the Grote Rede had an active connection through the "Passe du Nord-Est" (Noordoostpas) with the Westdiep swale. As VAN VEEN remarked in 1936, according to its shape the Grote Rede can be assigned an ebb-dominated swale, whilst the Westdiep is a clear flood-shaped swale. In nature, opposing swales will always try to avoid each other, possibly leading to an uppiling of sand at the interaction zone. In later publications, this mechanism is referred to as a mutually evasive system. (e.g. VAN VEEN (1936; 1950); CASTON (1972); ROBINSON (1966) and HARRIS & COLLINS (1991)).

It should be stressed that the Stroombank was a shoreface-connected ridge (i.e. STESSELS (1866)) until the bank was cut off due to dredging activities to open the entrance to the harbour of Oostende. Till now, the Kleine Rede still shallows in an eastern direction leading to a possible trap for western originating sediments. Note the linear shape of the Stroombank especially in comparison to the Nieuwpoort Bank.

2.5 Conclusions

In the present chapter an overview has been given of the complexity of the study area. From the literature and reports, it is clear that the evolution of a coastal system is dependant on a variety of factors which can all be interrelated.

To unravel the complexity of an environment dominated by the combined action of currents and waves, a variety of parameters and their mutual dependencies have indeed to be investigated, taking into account natural as well as anthropogenic controls. Within the framework of the present study, this is primarily done on the basis of investigating changes in the sedimentary pattern and relating those to hydrodynamical and meteorological parameters. However, as morphological change is part of a natural system, it is merely its rate that is important.

Results are split up into three chapters. Firstly, the competence of hydrodynamical forces is evaluated on the basis of available current meter data; secondly and thirdly the spatial and temporal variability of the coastal system is discussed. The final chapter is a synthesis and will highlight some aspects of the research questions together with future perspectives.

In the next chapter, an overview of the data collected throughout the study is presented, together with an outline of the techniques involved.

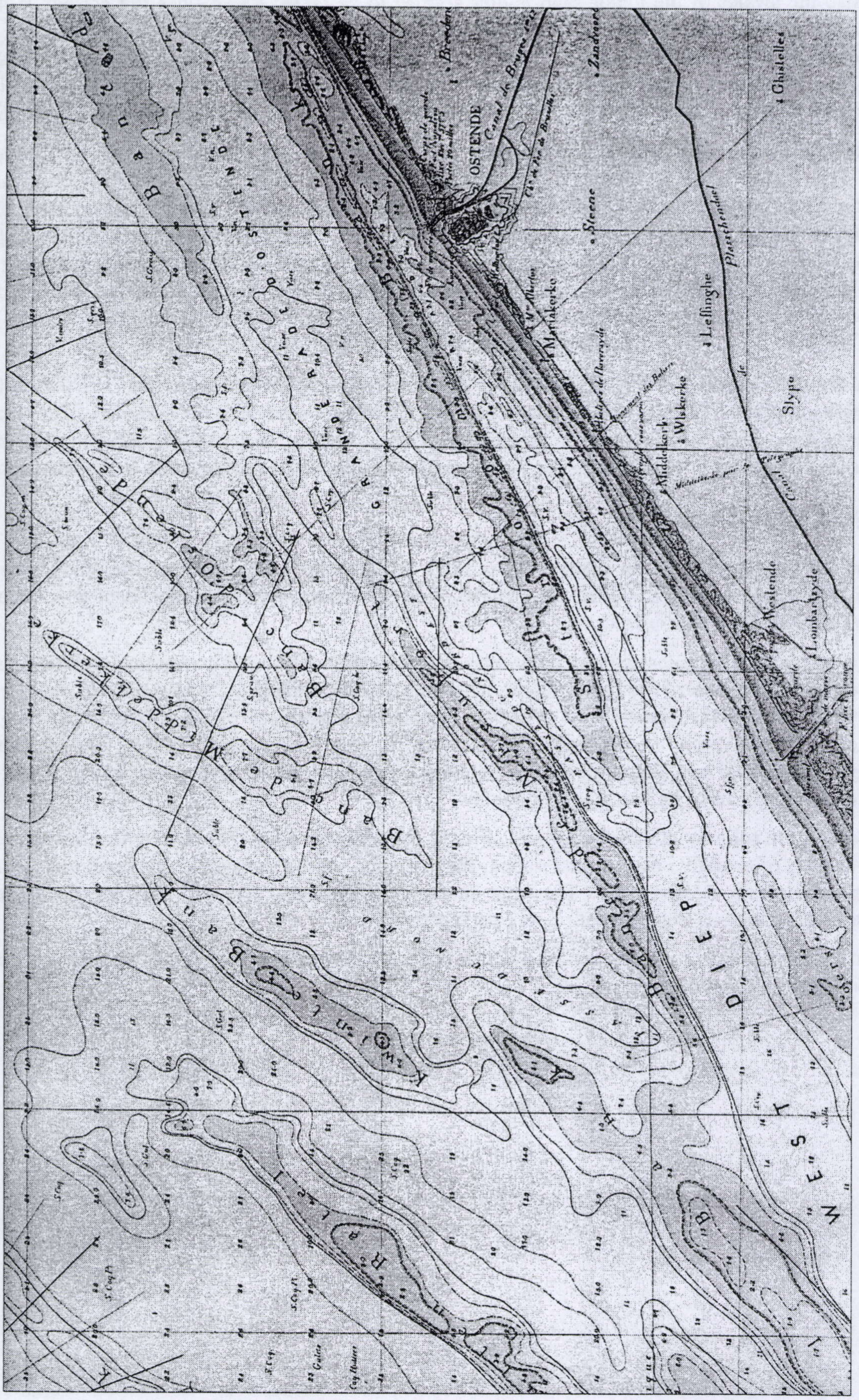


Figure 2.09 - Extract of the hydrographic map of STESSELS (1866). The blue colour corresponds with areas shallower than - 6 m (HYDROGRAFIE OOSTENDE (1996)).

3. DATA COLLECTION AND PROCESSING

3.1. Strategy and field observations

Most of the field data were obtained during campaigns on board the Belgian oceanographic research vessel *"Belgica"*; still, an important source of data was acquired through cooperation with other Institutes.

Under the supervision of Utrecht University (NL) and within the framework of the MASTII - STARFISH programme (HEYSE & DE MOOR (1996)), 115 boxcores were recovered along four transects perpendicular to the coastline (STOLK (1996)). As this set is spread over the near coastal area and includes the swales, the sandbanks and the shoreface, they were used as complementary evidence within the present investigation.

A quantitatively and qualitatively important dataset was obtained, through a synergism with the *"Marine Biology Department"* of Gent University. As their objectives partly met the needs of the present research, it was possible to study the spatial and temporal variability of the surficial sediments of the shallow Coastal Banks with the "*Oostende XI*" and "*Jacqueline*". Over a one-year cycle, the surficial sediments of the Stroombank and the Nieuwpoort Bank were sampled on a monthly basis. Later, the sampling was concentrated onto a transverse profile, incorporating both sandbanks.

A detailed investigation of the sediment and morphodynamics concentrated upon four environments; two in the near coastal area and two in the interaction zone with the more offshore Flemish Banks: (i) centrally, the near coastal Baland Bank was monitored due to its unique configuration and higher dynamics; (ii) the Westdiep swale and the western extremity of the Stroombank were surveyed to investigate sediment transport pathways; (iii) the southern end of the Middelkerke Bank was included, because of the intensive ground truthing database made possible by several MAST projects (DE MOOR & LANCKNEUS (1993); HEYSE & DE MOOR (1996); O'CONNOR (1996)); and finally (iv) a small sandbank, the Ravelingen, was introduced because of its similarity with the more coastal Baland Bank.

Tracklines over the Baland Bank were spaced 50 m apart, more or less perpendicular to the strike of the bedforms; the southern part of the Middelkerke Bank was covered with lines 75 m apart. As the Ravelingen was only optionally surveyed whenever an extra high water window was available, the tracklines were sailed at a 150 m spacing. However, during three of the campaigns, time-schedule allowed a more detailed survey to be undertaken.

The coastal system as a whole has been characterised by means of sampling and bathymetrical surveys. For the general surveys, tracklines were selected in relation to the DECCA chain network, lying obliquely to the shoreline.

For the planning of the research activities, a 1 m contoured bathymetric workchart was used; this map was compiled by EUROSENSE on the basis of depth measurements carried out by the *Belgian Waterways Coast Division* (AWK) (HOUTHUYS & VAN SIELEGHEM (1993)).

Table 3.01 provides an overview of all the data relevant to this study. Figure 3.01 and 3.02 give a visualisation of the sailed profiles and of the sampling points.

Referring to the research objectives outlined in the introductory chapter, a number of techniques were used to study the dynamical behaviour of a shallow-marine coastal system; in the following text, some of them will be briefly discussed. If necessary for the coherency of a specific topic, more detail will be provided in the subsequent chapters.

Table 3.01 - Summary of the data used in the present investigation.

reference	begin	end	research vessel	data type
ASMB94	1994-07-19	1994-07-27	*Navicula (NL)*	Boxcores (115)
ST9504	1995-04-04	1995-04-04	*Oostende XI*	Van Veen grabs (11), bathymetry reference profile
ST9505	1995-05-04	1995-05-04	*Oostende XI*	Van Veen grabs (14)
ST9506	1995-06-19	1995-06-19	*Oostende XI*	Van Veen grabs (15)
ST9507	1995-07-05	1995-07-05	*Oostende XI*	Van Veen grabs (6)
ST9508	1995-08-07	1995-08-07	*Oostende XI*	Van Veen grabs (16)
ST9510	1995-10-03	1995-10-03	*Oostende XI*	Van Veen grabs (14)
ST9511	1995-11-08	1995-11-08	*Oostende XI*	Van Veen grabs (16)
ST9512	1995-12-08	1995-12-08	*Oostende XI*	Van Veen grabs (21), bathymetry reference profile
VN9512	1995-12-11	1995-12-14	*Belgica*	Van Veen grabs (40), bathymetry, side-scan sonar
ST9601	1996-01-15	1996-01-15	*Oostende XI*	Van Veen grabs (14)
VV9602	1996-02-06	1996-02-09	*Belgica*	Van Veen grabs, bathymetry, side-scan sonar
ST9603	1996-03-13	1996-03-13	*Oostende XI*	Van Veen grabs (7), bathymetry reference profile
ST9604	1996-04-19	1996-04-19	*Oostende XI*	Van Veen grabs (14)
VV9605	1996-05-03	1996-05-10	*Belgica*	Van Veen grabs, bathymetry
ST9608	1996-08-21	1996-08-21	*Oostende XI*	Van Veen grabs (17)
VV9609	1996-09-23	1996-09-26	*Belgica*	Van Veen grabs (12), bathymetry, side-scan sonar
VV9611	1996-11-25	1996-11-27	*Belgica*	boxcores (4),Van Veen grabs (20+15), bathymetry
VV9612	1996-12-18	1996-12-18	*Belgica*	Bathymetry
ST9701	1997-01-22	1997-01-22	*Jacqueline*	Van Veen grabs (11)
VV9702	1997-02-24	1997-02-28	*Belgica*	Bathymetry
ST9704	1997-04-22	1997-04-22	*Jacqueline*	Van Veen grabs (7)
MV9704	1997-04-29	1997-04-30	*Belgica*	Bathymetry
VV9705	1997-05-05	1997-05-07	*Belgica*	Van Veen grabs (40), bathymetry, side-scan sonar
ST9708	1997-08-26	1997-08-26	*Jacqueline*	Van Veen grabs (10)
VV9709	1997-09-08	1997-09-12	*Belgica*	Van Veen grabs (30), bathymetry
VV9711	1997-11-03	1997-11-07	*Belgica*	Bathymetry
VV9712	1997-12-15	1997-12-18	*Belgica*	Bathymetry
VV9802	1998-02-02	1998-02-04	*Belgica*	Boxcores (10), bathymetry
VV9803	1998-03-23	1998-03-27	*Belgica*	Bathymetry
ST9804	1998-04-08	1998-04-08	*Oostende XI*	Van Veen grabs (13)
VV9806	1998-06-02	1998-06-03	*Belgica*	Van Veen grabs (7), bathymetry

Key: reference: internal prefix, year, month; begin and end: year, month and day.

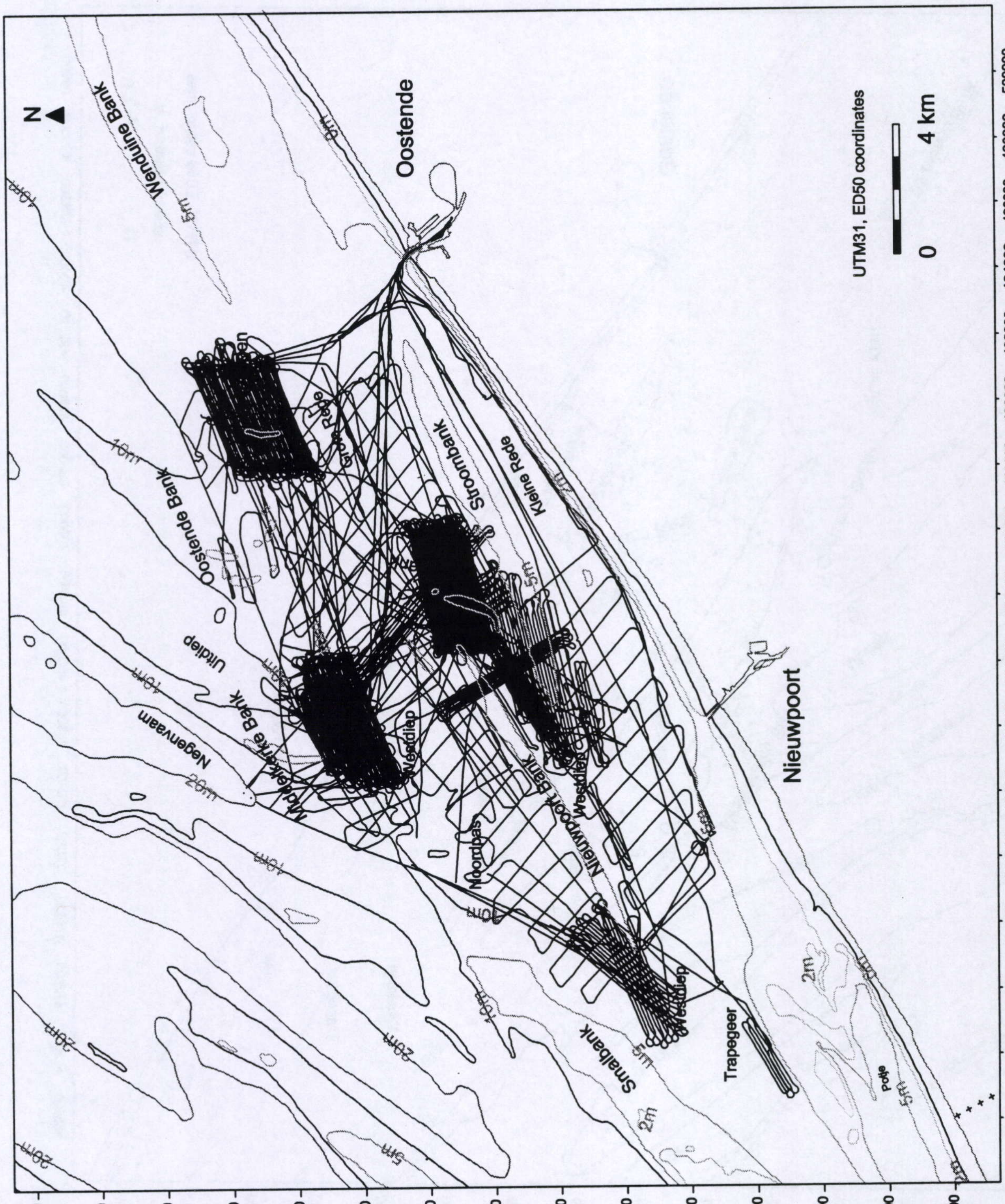


Figure 3.01 – Sailed profiles (bathymetry HYDROGRAFISCHE DIENST VAN OOSTENDE AFDELING WATERWEGEN KUST (1995))

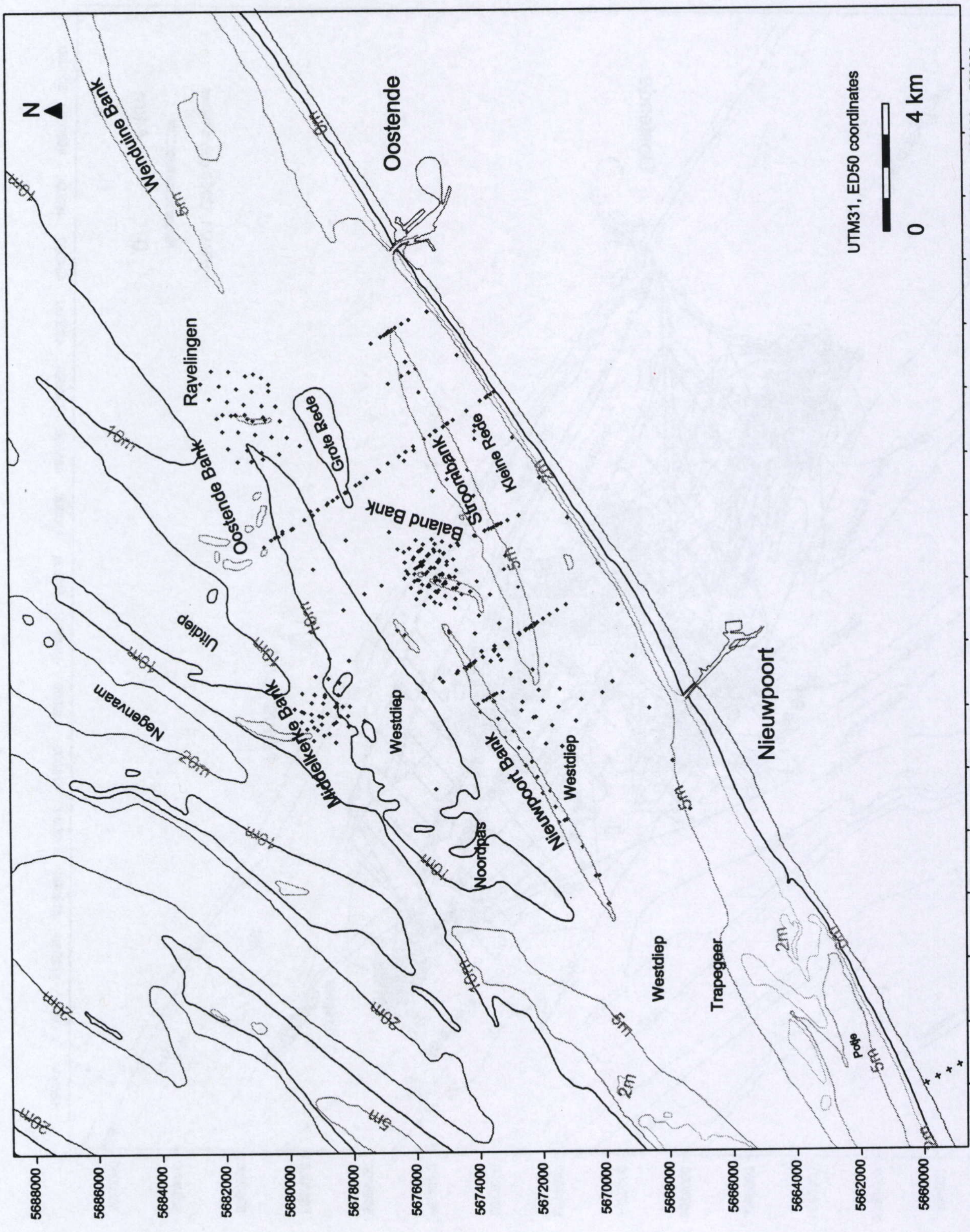


Figure 3.02 – Offshore sampling points (bathymetry HYDROGRAFISCHE DIENST VAN OOSTENDE AFDELING WATERWEGEN KUST (1995))

3.2. Onboard instrumentation, data acquisition and processing

Crucial to the whole process of data acquisition is the navigation and positioning. The research vessels involved in this project were all equipped with differential global positioning systems (DGPS). Tests of the SERCEL NR 103 DGPS on board of the *"Belgica"* showed an accuracy of 3 to 5 m (1-2 DRMS) (VAN ZIELEGHEM (1998)). The final processing of all the data was performed in ED50 coordinates (Hayford 1924 reference plane), as this is the standard for survey work on the Belgian continental shelf.

The offshore data consists primarily of echosoundings. On board the *"Belgica"*, a KRUPP ATLAS DESO 20, upgraded to a DESO 22, was available for use. Raw bathymetrical data (at 33 kHz and 210 kHz) were transferred to a TSS 320B heave compensator, so that both the analogue and digital recordings were corrected for the vertical movement of the ship. A ship speed of 8 to 10 knots was preferred for the bathymetric registrations.

On board of the *"Belgica"*, the acquisition of data from all the mounted instruments is centralised through the "*Oceanographic Data Acquisition System*" ODASII (BEHEERSEENHEID MATHEMATISCH MODEL NOORDZEE EN SCHELDE ESTUARIUM (1996)). The acquisition rate of navigation, positioning, bathymetry and sea water related parameters was preferably set to 2 Hz. More general parameters, such as wind data were recorded every 10 s.

Side-scan sonar records were collected to obtain textural and morphological information on the seafloor on the basis of the reflectivity differences of acoustic waves (FLEMMING (1976); BLONDEL & MURTON (1997)). Through cooperation with the "*Research Unit for Marine and Coastal Geomorphology*", University of Gent, it was possible to deploy a KLEIN towfish, equipped with a 500 kHz transducer (KLEIN ASSOCIATES (1990)). During the surveying, an optimal ship speed of 4 knots was maintained. All the data were recorded as well analogue (KLEIN digital sonar recorder model 595) as digitally using Delph processing software (ELICS). The final processing and mosaicing was however done with TRITON (Vista) processing software owned by the Company MAGELAS. Corrections for the height of the fish above the seabed (the slant range), lay-back and the vessel speed were taken into account.

Sediment sampling was performed using a Van Veen grab sampler, allowing the characterisation of the surficial sediments (upper 10 cm) of the study area. Although the obtained samples are fully disturbed, the advantage is mainly its effectiviness; hence an important number of samples can be taken in a relatively short period of time.

Under the supervision of Utrecht University (STOLK (1993)), the sedimentary structures of the upper 30 to 50 cm of the seafloor were studied using a Reineck type boxcorer (™ Netherlands Institute for Sea Research). On board the "*Navicula*", summer of 1994, a coring device was used that allowed the extraction of a rectangular volume of sediment (0.3*0.2 m) with a maximum penetration of 0.5 m (on average 0.2–0.3 m). On the *"Belgica"*, boxcores were recovered during the November 1996 and February 1998 campaigns. As the boxcoring device was cylindrical, sub-cores were taken that were described and photographed onboard. Sediment samples were taken from the surface and at specific levels within the cores.

Data on the suspended particulate matter in combination with an acoustic doppler current profiler (ADCP) were collected in the Baland Bank area in September 1998. These results will however be attempted elsewhere.

From the diversity and the amount of data involved in the present study, an integrated methodology was sought for an optimised processing of the data. Hence, all data were integrated into databases, enabling a dynamical interaction between the different data sources. Figure 3.03 demonstrates the relationships between the different databases.

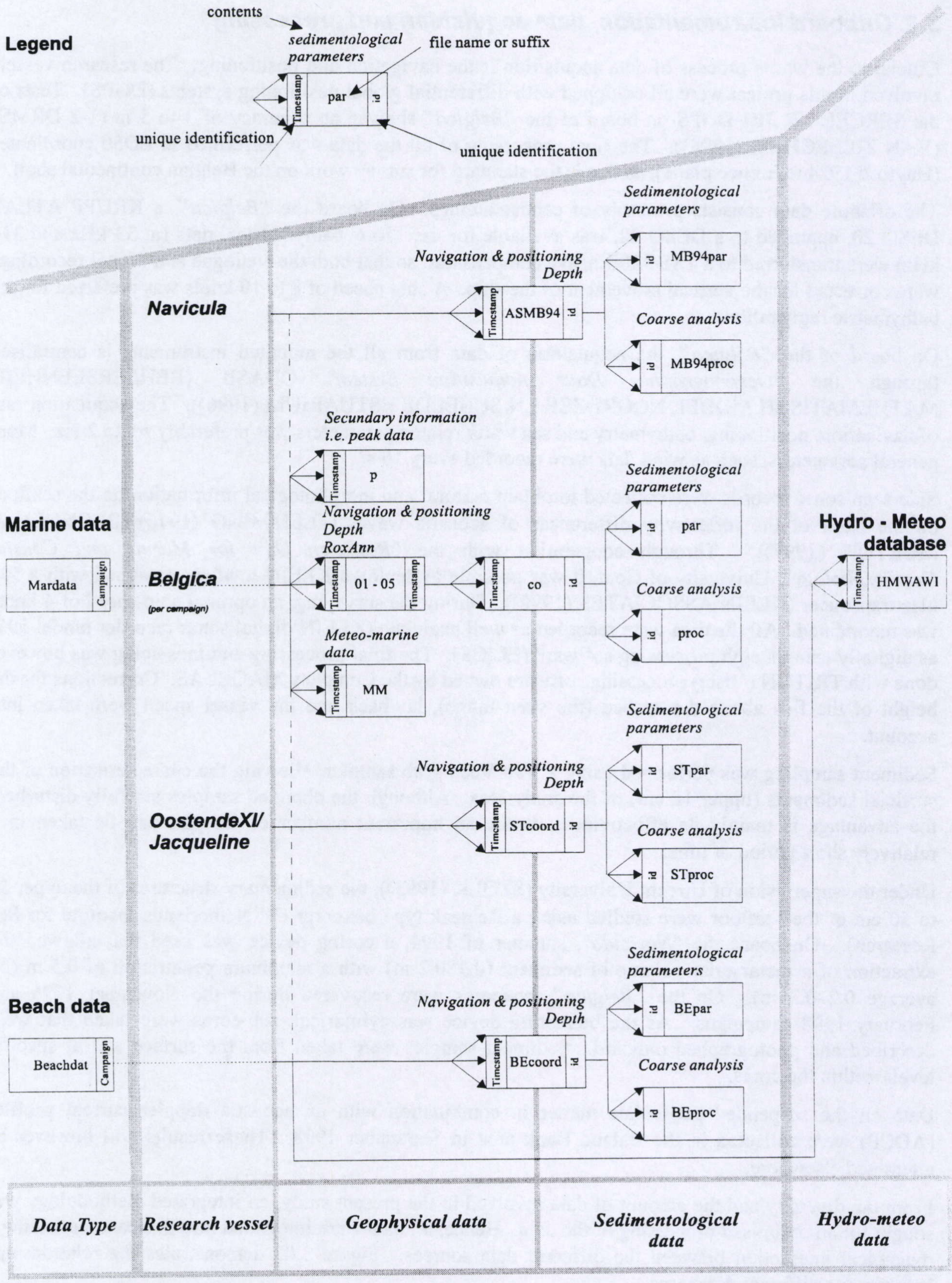


Figure 3.03 –Structure of database and internal relationships.

3.3. Laboratory analysis

3.3.1. Analysis of the acoustical data

The raw navigation, positioning and bathymetrical data, acquired on board the *"Belgica"* were further processed to allow a morphological interpretation of the research area. A coherent methodology was worked out to uniformly process the data. Programmatical interaction within the database environment allowed a verification of the data and an addition of fields to facilitate and optimalise further processing. The geographical latitudes and longitudes were converted into UTM31-ED50 coordinates and corrected for offsets. As the timestamp was considered the key field throughout the research, an uniformisation of its format was accomplished for all the data sources, hence enabling their relations.

On the basis of the procedures described in VAN CAUWENBERGHE et al. (1992), the "*Research Unit for Marine and Coastal Geomorphology*", University of Gent, developed a tidal correction programme for the Belgian continental shelf. All echosounding data were hence corrected for the tides and were reintegrated into the database.

Using WINDOWS based software and programming, the data were further processed into profiles. A graphical interface with a workspace in real coordinates was preferred as this allowed an easy transfer with the database structure. The exact locations of the morphological features could hence easily be exported to the database where an extra verification was executed. The tidally corrected echosounding data was processed into digital elevation models and derivatives.

3.3.2. Analysis of the sedimentological data

The surficial sediments sampled on board the different research vessels were analysed according to the same procedures. After drying the bulk sediment, samples were mechanically split into a representative sub-sample. Grain-size analyses were performed using a laser diffractometer (*Malvern Inc.*). The principles of laser diffraction spectroscopy are outlined in McCAVE & SYVITSKI (1991). This technique was chosen for its efficiency and its ability to measure the whole grain-size range from silt to sand. As the majority of the sediment samples consisted of an unimodal distribution, with a median value within the sand fraction, only one lens (600 mm; theoretical range: 11.6 – 1128 µm) was needed during the measurement procedure. Moreover, the use of the instrument is justified, as the upper limit of the grain-sizes approximated 710 µm and the finer fraction did not exceed 20 % of the total sample (SEVENS & JACOBS (1990)).

Samples having a high silt-clay to sand ratio were analysed using sieves (1/4 ϕ), in combination with a Sedigraph X-ray instrument. It should be noted that a laser diffractometer measures the distribution of the mean size of particles, whilst the sieves determine the diameter of the smallest particle (SINGER et al. (1988)). As the fine-grained sediments are primarily located in the deeper parts of the study area, they are used to characterise that specific environment. Only samples pertaining to an unimodal physical system, and thus analysed with a laser diffractometer, are compared relative to each other in a series analysis.

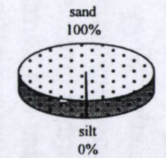
Sedimentological parameters were calculated, according to the graphical method of FOLK & WARD (1957) and the moment statistics (SEWARD-THOMPSON & HAILS (1973)). In addition, the mean of only the grain population was calculated. KRANCK & MILLIGAN (1991) have pointed out that it is necessary to separate the floc population, as flocs behave differently than grains and show internally an uniform distribution. This observation means that a normal grain-size analysis would give a combination of a grain population, and the internal grain distribution within the flocs. In this case, the distribution curve shows an important tail and a smearing of the standard deviation. An example of a grain-size analysis sheet is given in Figure 3.04.

sample: 9705BB.010

class		µm upper limit	-	µm lower limit	phi	cumulative volume%	volume%
gravel		*none*	-	16000.00	-4.00	0.00	0.00
		16000.00	-	13454.34	-3.75	0.00	0.00
		13454.34	-	11313.71	-3.50	0.00	0.00
		11313.71	-	9513.66	-3.25	0.00	0.00
		9513.66	-	8000.00	-3.00	0.00	0.00
		8000.00	-	6727.17	-2.75	0.00	0.00
		6727.17	-	5656.85	-2.50	0.00	0.00
		5656.85	-	4756.83	-2.25	0.00	0.00
		4756.83	-	4000.00	-2.00	0.00	0.00
		4000.00	-	3363.59	-1.75	0.00	0.00
		3363.59	-	2828.43	-1.50	0.00	0.00
		2828.43	-	2378.41	-1.25	0.00	0.00
		2378.41	-	2000.00	-1.00	0.00	0.00
sand	very coarse	2000.00	-	1681.79	-0.75	0.00	0.00
		1681.79	-	1414.21	-0.50	0.00	0.00
		1414.21	-	1189.21	-0.25	0.00	0.00
		1189.21	-	1000.00	0.00	0.00	0.00
	coarse	1000.00	-	840.90	0.25	0.50	0.50
		840.90	-	707.11	0.50	2.50	2.00
		707.11	-	594.60	0.75	6.92	4.42
		594.60	-	500.00	1.00	14.62	7.70
	medium	500.00	-	420.45	1.25	26.96	12.34
		420.45	-	353.55	1.50	40.58	13.63
		353.55	-	297.30	1.75	57.89	17.30
		297.30	-	250.00	2.00	75.20	17.32
	fine	250.00	-	210.22	2.25	88.37	13.16
		210.22	-	176.78	2.50	94.94	6.57
		176.78	-	148.65	2.75	97.10	2.17
		148.65	-	125.00	3.00	98.20	1.10
	very fine	125.00	-	105.11	3.25	98.92	0.71
		105.11	-	88.39	3.50	99.25	0.33
		88.39	-	74.33	3.75	99.48	0.23
		74.33	-	62.50	4.00	99.66	0.18
silt	very coarse	62.50	-	52.56	4.25	99.69	0.03
		52.56	-	44.19	4.50	99.79	0.10
		44.19	-	37.16	4.75	99.80	0.01
		37.16	-	31.25	5.00	99.83	0.03
	coarse	31.25	-	26.28	5.25	99.90	0.07
		26.28	-	22.10	5.50	99.90	0.00
		22.10	-	18.58	5.75	99.90	0.00
		18.58	-	15.63	6.00	99.90	0.00
	medium	15.63	-	13.14	6.25	99.90	0.00
		13.14	-	11.05	6.50	99.90	0.00
		11.05	-	9.29	6.75	99.91	0.00
		9.29	-	7.81	7.00	99.91	0.00
	fine	7.81	-	6.57	7.25	99.91	0.00
		6.57	-	5.52	7.50	99.92	0.00
		5.52	-	4.65	7.75	99.92	0.00
		4.65	-	3.91	8.00	99.92	0.00
	very fine	3.91	-	3.28	8.25	99.93	0.00
		3.28	-	2.76	8.50	99.93	0.00
		2.76	-	2.32	8.75	99.93	0.00
		2.32	-	1.95	9.00	99.94	0.00
clay		1.95	-	0.06	14.00	100.00	0.06

Percentiles	Grain-size Phi-units	µm
1	0.31	805.02
3	0.53	693.32
5	0.64	641.05
10	0.85	554.77
15	1.01	497.34
16	1.03	490.40
20	1.11	463.61
25	1.21	432.16
30	1.31	404.49
35	1.40	379.57
40	1.49	356.18
45	1.56	338.25
50	1.64	321.73
55	1.71	306.02
60	1.78	291.08
65	1.85	276.88
70	1.92	263.36
75	2.00	250.51
80	2.09	234.70
84	2.17	222.66
85	2.19	219.75
90	2.31	201.35
95	2.51	175.86

Lithological fractions	
fraction	%
gravel	0.0
sand	99.7
silt	0.3
clay	0.1



moment measures					in µm	
mean	=	1.63	=>		323.20	
sorting	=	0.66	=>	511.29	--68.27%--	204.30
skewness	=	2.85		upper limit		lower limit
kurtosis	=	41.85				
graphical parameters					in µm	
mean	=	1.61	=>		327.51	
sorting	=	0.57	=>	485.36	--68.27%--	221.00
skewness	=	-0.07		upper limit		lower limit
kurtosis	=	0.97				
moment measures without flocculated population						
volume% population	=	99.90			in µm	
mean	=	1.62	=>		325.09	
sorting	=	0.60	=>	493.22	--68.27%--	214.27
skewness	=	0.45		upper limit		lower limit
kurtosis	=	4.86				

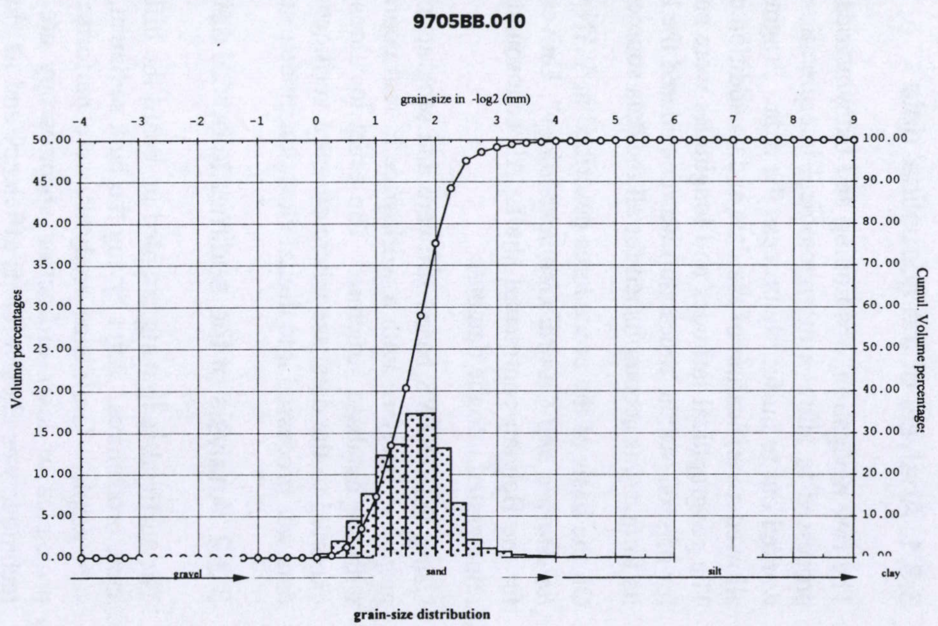


Figure 3.04 - Grain-size analysis sheet.

Sub-samples taken from the boxcores were analysed in the same manner. The main reason for their deployment was to obtain a relatively undisturbed volume of sediment, representing the upper 30 cm (sand) to 50 cm (mud) of the seafloor. A detailed study of the vertical profile permits a characterisation of the sedimentary processes (i.e. HOWARD & REINECK (1972); REINECK (1976); REINECK & SINGH (1980); ALLEN (1984); HOUTHUYS (1990); DALRYMPLE (1992); WALKER & PLINT (1992) and VAN DE MEENE et al. (1996)). Rectangular boxcores (Reineck type) allow the study of sediments in three dimensions. After removing both the front and side panels from the core, the sediment surface was cleaned and cut at a mild angle. Lacquer was poured over the sediment (according to the method of BOUMA (1969)). Following a fixation period of about 2 hr, a coarse layer of cloth could be placed over the exposed surface using the same viscous substance. After a drying period of about 3 hr, the top 1-4 mm of sediment adheres to the cloth; this was then removed to produce a peel. If stuck to a wooden panel, the structural elements could be highlighted (i.e. foresets, burrows, clasts) (STOLK (1993)). The whole process of making lacquer peels was undertaken aboard the "*Navicula*"; later on, they were described and photographed. Due to their limited size (30 cm), the sub-cores retrieved from the boxcores obtained with the *"Belgica"* were lacquer-peeled and further processed in the laboratory.

The sample coordinates were corrected for the position of the sampling device, relative to the ships antenna.

3.3. Analysis of hydrodynamical and meteorological data

Studying causal relationships in morphological change implies a necessity to link the observations with the prevailing hydrodynamical and meteorological conditions. From the observation period, a database was created containing information on the wave climate and the wind characteristics. The data were provided by the *Belgian Waterways Coast Division* (AWK) at Oostende. Once again, the data was transformed to already defined standards, in order to facilitate the relationships with other data sources. The measuring pile at the Westhinder (Hinder Banks, Fig. 1.01) was chosen for the hydrodynamical parameters, as this proved to be the most stable offshore platform (WENS et al. (1990)). Meteorological conditions were derived from the meteopark at Zeebrugge (Fig. 2.08). Data from the wave buoy located along the Trapegeer (Fig. 2.02) were also used, as this was the nearest station to the study area. The wind data were processed into frequency distributions and wind roses (Chapter 6). The database structure allowed an easy transfer of the relevant parameters for use in the interpretations.

3.4. Current meter data analysis and processing

3.4.1. Introduction

In order to characterise the sediment transport potential in the study area, it was decided to evaluate the existing current meter data from external institutes. Through the *Belgian Waterways Coast Division* (AWK) it was possible to obtain data collected within the framework of the Current Meter Atlas (VAN CAUWENBERGHE (1992)). *The Management Unit for Mathematical Modelling of the North Sea and Scheldt Estuary* provided a dataset, consisting of two locations adjacent to the study area, but covering a complete year cycle.

3.4.2. Data analysis

The data analysis of the raw current meter data was performed by the *Belgian Waterways Coast Division* (AWK). As outlined by VAN CAUWENBERGHE (1992), the speed and direction of the currents for each spring and neap tide were available hourly, representing averaged values over 7 successive tides. The first high water of the data series was preceded by a full or new moon or first or last quarter. The mean current speed and direction at mid-tide are the arithmetic mean of the corresponding spring and neap tide values at that particular location. Measurements biased by any meteorological forcing are suppressed; so the data only represent fair-weather conditions. The currents are referenced to Zeebrugge, 6 hours before (a) and after (p) its high water. The data series were supplemented by values at flood/ebb maxima and minima, with their corresponding time-lag relating to high water at Zeebrugge. The *in-situ* velocities were recalculated to surface velocities and corrected for the 18.61-yr cycle of regression of the lunar nodes. Each hourly depth measurement has been corrected for tidal range. Table 3.02 gives an overview of the data used in the framework of this study, listing the characteristics of the deployments. The tidal current ellipses, at each of the locations were shown earlier in Figure 2.02 (Section 2.2).

Table 3.02- Overview of the current meter data relevant for this study (Source data: AWK) (For location, see Figure 2.02).

reference	location	northing UTM (m)	easting UTM (m)	begin (y-m-d)	end (y-m-d)	hsitu (m)	mllws (m)	instrument
01/60	Grote Rede	5681824	494653	1960-08-24	1960-09-05	3.8	-8	SR
03/61	Kleine Rede	5673557	487330	1961-03-16	1961-04-05	3.6	-8.4	SR
05/62	Westdiep	5669163	473200	1962-05-03	1962-05-20	3.7	-10	SR
15/65	Ravelingen	5683071	488070	1965-08-19	1965-09-05	3.3	-10.6	SR
18/66	Outer Nieuwpoort Bank	5677346	480843	1966-08-24	1966-09-07	2.4	-15	SR
19/67	Westdiep	5665579	467973	1967-04-24	1967-05-09	3.4	-16.6	SR
20/67	Noordpas	5673110	474715	1967-05-09	1967-05-23	3.4	-10.9	SR
28/69	Westdiep	5671077	480354	1969-07-04	1969-07-17	3	-9.3	SR
31/70	Grote Rede	5679361	489263	1970-07-30	1970-08-13	3	-10.6	SR
33/70	Noordoost Pas	5672502	479331	1970-10-07	1970-10-29	3	-11.2	SR
36/71	Near Oostende	5676788	494474	1971-09-03	1971-09-16	3	-6	SR
02/74	Trapegeer	5665720	470209	1974-06-05	1974-07-02	3	-7.3	FS
03/74	Potje	5662534	470832	1974-06-05	1974-07-02	3	-6	FS
05/74	WK70 Westdiep	5670443	476915	1974-08-31	1974-09-19	3	-11.3	FS
06/74	Inner Stroombank	5676852	492709	1974-08-13	1974-08-28	3	-6	FS
07/74	Oostende Bank, West	5680090	482365	1974-08-13	1974-08-28	3	-9.3	FS
08/74	Negenvaam (MB)	5683806	480054	1974-08-13	1974-08-28	3	-21.1	FS
01/75	Outer Stroombank	5678154	490443	1975-06-12	1975-07-02	3	-8.5	SR
09/82	WK57 near Oostende	5676419	493697	1982-08-02	1982-08-28	3	-5.2	FS
01/87	WK3 Oostduinkerke	5667169	476764	1987-03-13	1987-04-03	3	-9.7	FS
02/87	Stroombank, West	5671045	480529	1987-03-13	1987-04-03	3	-9.4	FS
03/87	Trapegeer	5665811	470404	1987-05-11	1987-06-02	3	-8.9	FS
07/87	Smalbank	5670456	468586	1987-05-11	1987-06-02	3	-6.5	FS
01/88	Near Oostende E	5676788	494590	1988-06-27	1988-07-23	3	-5.9	FS
02/88	Near Oostende W	5676326	493426	1988-06-27	1988-07-23	3	-5.9	FS
01/89	Potje	5662473	470773	1989-11-13	1989-12-11	3	-6.6	FS
02/89	Stroombank, South	5672944	485543	1989-11-13	1989-12-11	3	-10	FS

Key: Northings and eastings were calculated from geographical coordinates using the ED50 ellipsoid. Hsitu is the elevation of the current meter above the sea bed. MLLWS represents the depth relating to the mean lowest low water on a spring tide for each location. SR: Schaufelrad; FS: Flachsee (propeller type self-recording current meters). Position fixing was established on the basis of DECCA Main Chain, which has an error estimate of a few hundred meters.

The data provided by *the Management Unit for Mathematical Modelling of the North Sea and Scheldt Estuary* was only used for presentation purposes. The data consisted of vector-time series of current speed and direction, resolved into east-west (u) and north-south (v) components (Fig. 4.03, 4.04). It is assumed that the flow is positive (+) in an easterly and in a northerly direction. However, a further analysis of the data will be attempted elsewhere.

3.4.3. Model calculations

3.4.3.1 Introduction

In order to evaluate the sediment transport capacity on the basis of the current meter data, a general procedure was sought to perform sediment transport calculations under the influence of tidal currents and waves. A practical approach for solving bedload, suspended and total load equations was adopted from SOULSBY (1997). This book provides an overview and discussion of empirical formulae, together with an outlined procedure to calculate the effects of currents and waves alone, and their combined action. The references cited are mainly adopted from SOULSBY (1997).

The current meter measurements coupled with the empirical formulae, allow a regional description of the sediment movement to be established. It should be emphasised however, that the analysis only provides qualitative results; these give an indication of transport rates. This is mainly due to the nature of the tidal current meter data, in the absence of *in-situ* wave data. Moreover, the sensitivity of the different formulae, to a large number of variables, inhibits any quantitative predictions. The methods utilised are based upon the assumption that conditions are horizontally-uniform, steady in time, with an inexhaustible supply of sediment. This implies that they are meant to calculate the equilibrium or saturated, sediment transport (SOULSBY (1997)). In the marine environment, such conditions are not typical due to the irregular topography, comprising sandbanks and the effect of the nearby coastline. The spatial and temporal changes will primarily affect suspended load transport, with a largest sensitivity for the finer grain-sizes.

The sediment transport calculations apply only for sand-sized material; if > 10 % of the sediment is finer than 0.062 mm, the effect of electrochemical and biological cohesion becomes important and may bias the results.

The sediment texture information required for the transport calculations was extracted from the sedimentological database collected throughout the present investigation. When needed external sources were consulted. As most of the current meter locations (Figure 2.02) are within navigational channels associated with rather high currents, the seafloor may be rippled, but is devoid of larger bedforms. When in doubt, the site was surveyed during the June campaign of 1998 (9806). Only the stations 07/74 and 07/87 pertaining to the Flemish Banks (Fig. 2.02), are likely to be related to larger dunes. In this case the current speed might be more variable, implying that the bedforms cannot fully adapt to the flow; thus, the formulae might turn less reliable (SOULSBY (1997)).

On the basis of the available current meter data, in the absence of detailed wave data, it was decided to calculate the effect of currents alone over the complete data set. The assumptions underlying the calculations are that under fair-weather conditions wave activity is minimal, compared to the mean flow at the recording sites. Indeed, giving an input of the dominant significant wave height Hs of 0.5 m and a corresponding period Tz of 3.5 s, which is characteristic for a location nearby, both procedures (currents alone and combined currents and waves) generate approximately the same results.

As the current meter data is stored in a database environment, all calculations were solved using the same programming approach. This allowed one-point values, or an array of values, in order to test specific conditions.

3.4.3.2 Predictions of sand transport from current meter data

In the following section, an overview will be given of how the sediment transport calculations were performed. However, a detailed description of the procedures followed to calculate the effect of currents alone and their interaction is not included; this is fully based upon the methodology and recommendations outlined in SOULSBY (1997). Only a few formulae will be discussed, as these are critical to the whole procedure. Variables are annotated within the text, the first time they are used. The procedure followed to estimate the combined action of currents and waves is outlined in Appendix B.

Current meter data from each of the stations are incorporated into empirically-derived formulae, to predict the sediment transport rates and directions. As the height of the current meters above the sea bed varied between 3 m and 3.8 m, it was decided to convert the *in-situ* velocities to depth-averaged currents using a power-law velocity profile (SOULSBY (1997)). Regarding the height of the current meters, a conversion of the velocity to values 1 m above the bed was regarded to be inaccurate, due to localised effects.

$$U(z) = \left(\frac{z}{0.32h}\right)^{1/7} \overline{U} \quad \text{for } 0 < z < 0.5h \quad \text{or} \quad U(z) = 1.07\overline{U} \quad \text{for } 0.5h < z < h$$

where

$U(z)$ = *in-situ* velocity (m/s);
z = depth of current meter above the bed (m);
h = total water depth (m) and
$\overline{U}$ = depth-averaged velocity (m/s).

Subsequently, the median grain-size is taken into account to calculate the threshold of motion. The philosophy behind the whole procedure is the determination of the bed shear stress, as this is the force controlling sediment transport.

The total bed shear-stress (τ_{0s}) acting on the bed is dependant upon: the *skin friction,* produced by and acting on the sediment grains; *the form drag,* produced by the pressure field associated with the flow over ripples and/or larger features on the bed (associated with intense turbulence which diffuses the suspended sediment up into the flow); and a *sediment transport* component, caused by the momentum extracted by the flow to move the sand grains (at very high flow speeds, with intense sheet flow). This situation applies to currents and waves alone and their interaction. It is the total bed shear stress that corresponds to the overall resistance of the flow, determining the turbulence intensities which influence the diffusion of suspended sediment to higher levels in the water column (SOULSBY (1997)).

Initiation of motion and suspension

For the threshold current speed for any non-cohesive sediment, SOULSBY (1997) recommends the following formula:

$$\overline{U}_{cr} = 7\left(\frac{h}{d_{50}}\right)^{1/7} \left[g\,(s-1)\,d_{50}\,f\,(D_*)\right]^{1/2} \quad for \quad D_* > 0.1$$

$$f\,(D_*) = \left(\frac{0.30}{1+1.2\,D_*}\right) + 0.055\left[1-\exp\left(-0.020\,D_*\right)\right]$$

where

D_* = dimensionless diameter

$$D_* = d\left[\frac{g\,(s-1)}{\nu^2}\right]^{1/3};$$

$\overline{U}_{cr}$ = threshold current speed (m/s);
d = grain diameter (m) (i.e. d_{90} is the grain diameter for which 90 % of the grains is finer);
g = acceleration due to gravity (m/s²);

s = ratio of densities of sediment (φ_s) and water (φ_w) (φ_s = 2650 kg/m³ ; φ_w = 1027 kg/m³) and
ν = the kinematic viscosity of water (m²/s).

For current speeds or wave conditions significantly above the threshold of motion, sand is entrained from the bed and into suspension, where it is carried at the same speed as the current (SOULSBY (1997)). For increasing values of the bed-shear velocity (u_*), the particles will be moving along the bed by more or less regular jumps (saltations). When the value of the bed-shear velocity becomes comparable to that of the particle fall velocity (w_s) (u_* equals w_s, in the criterion of BAGNOLD (1966)), the sediment particles may enter into suspension. Based upon experiments carried out by DELFT HYDRAULICS (1982), the critical flow conditions for initiation of the suspension were defined as the stage of flow at which particles perform a jump length larger than about 100 particle diameters. From these results, VAN RIJN (1993) has calculated the threshold Shields parameter for the initiation of suspension, as follows:

$$1 < D_* \leq 10: \quad \theta_{crs} = \frac{16}{D_*^2} \frac{w_s^2}{(s-1)gd_{50}}$$

$$\text{or for } D_* > 10: \quad \theta_{crs} = 0.16 \frac{w_s^2}{(s-1)gd_{50}}$$

where

θ_{crs} = threshold Shields parameter for initiation of suspension;
w_s = settling velocity (m/s).

The criterion of BAGNOLD may define an upper limit at which a concentration profile starts to develop, whilst the experiments (DELFT HYDRAULICS (1982)) merely represent an intermediate stage, at which locally turbulent bursts are able to lift sediment particles from the bed into suspension (VAN RIJN (1993)).

Sand transport under tidal currents alone

Throughout the years, a number of *bedload transport formulae* have been developed and proposed by several authors. Although most of them were originally designed for unidirectional currents, some are applicable in the marine environment and can be expressed in the form:

$$\Phi = \text{func}\,(\theta, \theta_{cr})$$

where

$\Phi = \dfrac{qb}{\left[g\,(s-1)\,d^3\right]^{1/2}}$, the dimensionless bedload transport rate;

$\theta = \dfrac{\tau_0}{g\,\varphi\,(s-1)\,d}$, the Shields parameter;

θ_{cr} = value of θ at threshold of motion;
qb = volumetric bedload transport rate per unit width (m²/s);
τ_0 = bed shear-stress for a flat bed (if bedforms are present the skin friction component is needed τ_{0s}) (N/m²) and
φ = water density (kg/m³).

SOULSBY (1997) presents an overview of the more commonly-used and recently-available transport formulae applicable to steady flows (MEYER & MULLER (1948); BAGNOLD (1963); YALIN (1963); WILSON (1966); ASHIDA & MICHIUE (1972); VAN RIJN (1984); MADSEN (1991); and NIELSEN (1992)). All the proposed bedload formulae were applied on the whole dataset in the present investigation. However, the formula of NIELSEN (1992) was retained for presentation as recommended by SOULSBY (1997):

$$\Phi = 12\,\theta^{1/2}\left(\theta-\theta_{cr}\right)$$

Total load transport rates were also calculated using a variety of empirically-derived formulae (ENGELUND & HANSEN (1972); ACKERS & WHITE (1973) and VAN RIJN (1984)). A discussion on the various formulae can be found in SOULSBY (1997). As the ENGELUND & HANSEN (1972) approach is used widely and reasonably accurate as total load equation, it is used for the presentation purposes together with the VAN RIJN (1984) formula. The full VAN RIJN (1984) method has also been used to calculate transport under the combined action of currents and waves, using the TRANSPOR programme (VAN RIJN (1993)). Moreover, it allows testing specific cases. To facilitate comparisons with other methods, the results are programmatically adapted and put in the same dimensions.

The ENGELUND & HANSEN (1972) formula states:

$$qt \quad = \quad \frac{0.04 C_D^{3/2}\,\overline{U}^5}{\left[g(s-1)\right]^2 d_{50}}$$

where

q_t = volumetric total transport rate per unit width (m^2/s) and
C_D = the drag coefficient, determined by the ENGELUND (1966) alluvial friction method.

Sand transport under the combined action of tidal currents and waves

For the investigation of the superimposed influence of waves upon sediment transport under currents alone, specific wave conditions were selected to calculate the combined effect of currents and waves; these were based upon the hydro-meteorological database provided by the *Belgian Waterways Coast Division (AWK)* (Section 3.3).

Naturally (irregular, or random) waves in the sea consist of a spectrum of wave heights, periods and directions. Assuming that higher waves contribute most to the sediment transport process, VAN RIJN (1993) regards the significant wave height (Hs), in combination with the peak period (Tp), as the characteristic wave parameters for representing sediment transport processes in "real" situations. However, since the hydro-meteorological database contains zero-crossing periods (Tz), this latter parameter is used in the calculations. A spectrum of waves can best be presented by the root mean square orbital velocity (U_{rms}) (SOULSBY (1997)). One of the most widely-used spectra is the JONSWAP spectrum, based upon a large number of wave measurements in the North Sea. SOULSBY (1997) provides an approximate curve, in terms of wave period and significant wave height to calculate the corresponding orbital velocity.

Together with currents, the most important hydrodynamic property of waves for sediment transport purposes is the bed shear stress they produce (SOULSBY (1997)). Hence, the total skin friction shear stress for waves and currents has now to be calculated. Firstly, both the shear stresses associated with currents and for waves alone is calculated; secondly, they are both related through a data-based model (DATA 2 or DATA 13 (SOULSBY (1997)), taking into account the angle between both of the forces. A mean bed shear stress (τ_m) is calculated, providing information on sediment diffusion; a maximum bed shear stress (τ_{max}) is related to the threshold of motion and entrainment.

Skin friction shear stress and form drag are calculated, for both the currents and the waves alone. The effective total roughness is calculated for the ripples with the largest height. The transport calculations are then repeated, using the effective total roughness.

The *mean bedload transport rate* is determined using the formula of SOULSBY (1997):

$$\Phi_{x1} = 12\,\theta_m^{1/2}\,(\theta_m - \theta_{cr}) \qquad \text{(dominance of currents)}$$

$$\Phi_{x2} = 12\left(0.95 + 0.19\cos 2\phi\right)\theta_w^{1/2}\,\theta_m \qquad \text{(dominance of waves)}$$

Φ_x = maximum of Φ_{x1} and Φ_{x2}

$$\Phi_y = \frac{12\left(0.19\,\theta_m\,\theta_w^2\,\sin 2\phi\right)}{\theta_w^{3/2} + 1.5\,\theta_m^{3/2}}$$

subject to $\Phi_x = \Phi_y = 0$ if $\theta_{max} \le \theta_{cr}$

where

$$\Phi_{x,y} = \frac{q_{bx,y}}{\left[g(s-1)d^3\right]^{1/2}}$$

qb = mean volumetric bedload transport rate, per unit width (m²/s);
qb_x = component of qb, travelling in the direction of the current (m²/s);
qb_y = component of qb at right angles to the current, in the same sense as the angle ϕ (m²/s);
θ_m = mean value of θ, over a wave cycle;
θ_w = amplitude of the oscillatory component of θ, due to waves;
ϕ = angle between the current direction and the direction of wave travel (°) and
$\theta_{max} = \left[(\theta_m + \theta_w\cos\phi)^2 + (\theta_w\sin\phi)^2\right]^{1/2}$.

The skin-friction components of θ_w, θ_m and θ_{max} are used for the rippled beds.

Total load transport, by waves combined with currents, is calculated using the Soulsby – Van Rijn approach (see above):

$$qt = A_s\,\overline{U}\left[\left(\overline{U}^2 + \frac{0.018}{C_D}U_{rms}^2\right)^{1/2} - \overline{U}_{cr}\right]^{2.4}\left(1 - 1.6\tan\beta\right)$$

$$A_{sb} = \frac{0.005h\,(d_{50}/h)^{1.2}}{\left[(s-1)\,g\,d_{50}\right]^{1.2}} \qquad \text{bedload component (units)}$$

$$A_{ss} = \frac{0.012\,d_{50}\,D_*^{-0.6}}{\left[(s-1)\,g\,d_{50}\right]^{1.2}} \qquad \text{suspended load component (units)}$$

$$A_s = A_{sb} + A_{ss}$$

where

qt = total sediment transport rate (m²/s);
$\overline{U}$ = depth-averaged current velocity (m/s);
$\overline{U}_{cr}$ = threshold current velocity, according to VAN RIJN (1984) (m/s);
U_{rms} = root mean square wave orbital velocity (m/s);

$$C_D = \left[\frac{0.40}{\ln(h/z_0)-1}\right]^2$$, the drag coefficient due to current alone;

β = slope of bed in a streamwise direction, positive if flow runs uphill (°) and

z_0 = 0.006 m = the bed roughness length.

The formula applies to the total (bedload and suspended load) sediment transport, in combined wave and current flows on horizontal and sloping beds. As the method is intended for use under conditions in which the bed is rippled, the bed roughness length should be set at 6 mm (SOULSBY (1997)). It must be stated that the effect of waves is only represented by the wave orbital velocity, not by the wave angle; however, waves can cause deviations in the sediment transport direction by up to 15° from the current direction (SOULSBY (1997)). The results of this approach can be compared with the output of the TRANSPOR programme (VAN RIJN (1993)). However, it should be noted that this program uses a minimum value of 0.01 m, for both the current- and wave-related bed roughness.

The results of the sediment transport calculations are presented in Chapter 4.

4. RESULTS: SEDIMENT TRANSPORT MODELLING

4.1. Introduction

Generally, the transport of sediment is affected strongly by hydrodynamical and meteorological forces. Due to the complexity of the forces involved and the large natural variability, the processes governing sediment transport are difficult to measure *in-situ*. Sediment transport studies are confined primarily to unidirectional flows (i.e. YALIN (1977)). However, a number of reviews relating to the inner shelf environment are presented by SMITH (1977), TAYLOR & DYER (1977), GRANT & MADSEN (1986), HORIKAWA (1988), DYER & SOULSBY (1988), CACCHIONE & DRAKE (1990), FREDSOE & DEIGAARD (1992), VAN RIJN (1993), WRIGHT (1995) and SOULSBY (1997).

The dominant mechanisms responsible for moving sands are currents (tidal, wind, or density driven) and waves, by which the combined action results in sediment motion. Sand can be moved in terms of entrainment, transportation and deposition (see below); these can take place at the same time and may interact with each other (Fig. 4.01). Due to the non-linear relation of sediment transport to the current speed, the net direction of sediment transport does not necessarily follow the direction of the residual water flow (YALIN (1977)). The sediment transport rate is defined as the amount of sediment, per unit time, passing through a vertical plane of unit width perpendicular to the flow direction (SOULSBY (1997)).

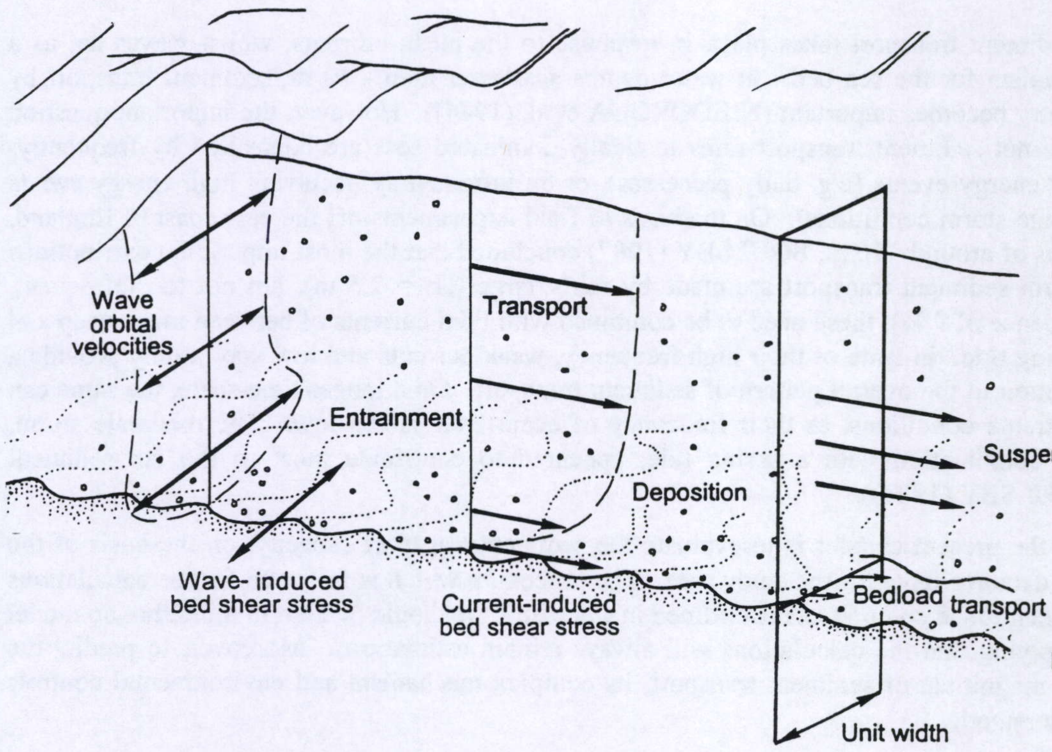


Figure 4.01 - Sketch of marine sediment transport processes (modified from SOULSBY (1997))

Entrainment results from friction exerted on the sea bed, by the current and/or wave action; turbulent diffusion is possible and may carry grains into suspension.

Transportation is caused by grains rolling, bouncing and sliding along the bed in response to friction or gravity in the case of sloping beds. Bedload transport is the dominant mode of transport for slow flows and/or large grains. If the flow is fast enough (or the waves sufficiently high) and the grains are sufficiently fine, sand will be put into suspension and will be transported as suspended load.

Deposition occurs when the grains come to rest, during bedload transport or by settling out of suspension.

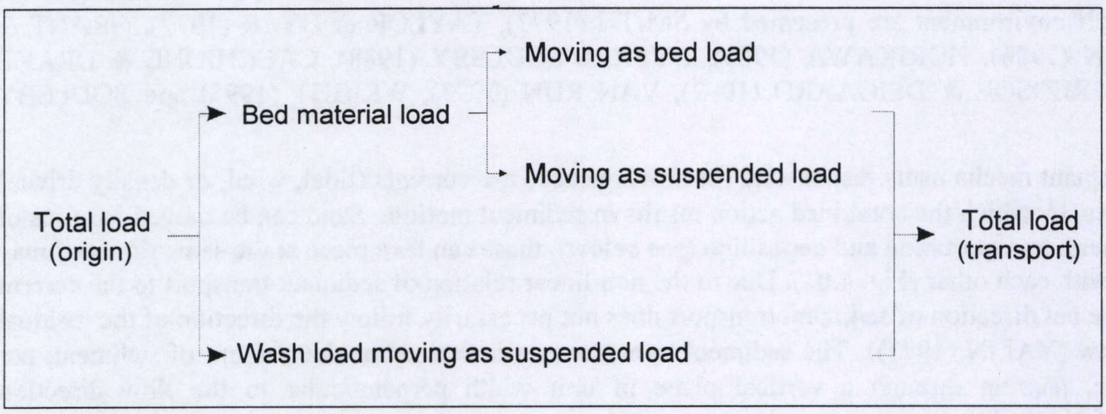


Figure 4.02 - Classification and definitions, in accordance with the ISO-standards (ISO 4363) (VAN RIJN (1993))

In general, sediment transport takes place in response to the mean currents, whilst waves act as a stirring mechanism for the sea bed. In water depths shallower than - 10 m, sediment transport by wave-asymmetry becomes important (NIEDORODA et al. (1984)). However, the important question is whether the net sediment transport rates in tidally-dominated seas are controlled by frequently-occurring low energy events (e.g. daily processes), or by infrequently occurring high energy events (such as extreme storm conditions). On the basis of field experiments off the east coast of England, in water depths of around - 10 m, SOULSBY (1987) concluded that the most important contributions to the long-term sediment transport are made by fairly large (Hs = 2.5 m), but not too infrequent, waves (exceedance of 9 %); these need to be combined with tidal currents of between mean neap and maximum spring tide. In spite of their high frequency, weak currents and low waves only provide a small contribution to the overall pattern of sediment transport. On a longer time-scale, the same can be said of extreme conditions, as their frequency of occurrence is too low. The moderate storm, preferably in combination with a spring tide, appeared to contribute most to the net sediment transport (SOULSBY (1987)).

The scope of the present chapter is to evaluate the sediment transport capacity, on the basis of the current meter data available for the study area. The procedure which is followed for the calculations of the above-mentioned components is outlined in Chapter 3. It should be kept in mind that no model is perfect, implying that the calculations will always remain estimations. Moreover, to predict the direction and magnitude of sediment transport, its complex mechanism and environmental controls should be understood.

4.2. "Fair-weather" sediment transport

In order to discuss the 'fair-weather' sediment transport, it is necessary to examine the flow patterns within the study area. In general, residual currents are controlled by the tidal flow, wind drag or by lateral density gradients (caused by salinity and temperature distributions). The tidally-driven residual currents are, however, dominant due to their persistent nature; they are influenced by local bottom conditions and by coastal topography (HOWARTH & HUTHNANCE (1984); ZIMMERMAN (1980) and YANG (1998)).

In Chapter 2, it was emphasised that the study area is dominated by strong flood- and ebb-dominated swales. Tidal current ellipses within flood-swales witness highly rectilinear currents, parallel to the depth contours. Swales exhibiting an ebb-dominated morphology are characterised by weaker currents, and the tidal ellipses are generally more rotary in nature (Fig. 2.02). Although it was not possible to investigate the hydrodynamics around the sandbanks in the study area in detail, there are a number of circumstances that indicate its complex pattern. The tidal current ellipses demonstrate that there is a clear asymmetry in the directionality, between the flood and the ebb tidal currents. The tidal currents are modified by the presence of the banks (BECK et al. (1991)). Due to the influence of adjacent sandbanks, a clear veering of the current (oblique to the banks' axis) can be observed. An example of this pattern is shown in Figure 4.03, representing a scatter plot of all the north-south and west-east components of the current velocity around the Nieuwpoort Bank, over a two year period (data source: MUMM). In comparison to the Trapegeer location (Fig. 4.04), it seems that sandbanks inhibit a well-developed flow pattern. In the latter case, the ebb component of the tide appears to be hindered by the adjacent morphology and is not capable of reaching velocities comparable to those at nearby locations. The tidal current ellipse is more rotary in nature, contrasting to the rectilinear currents characterising the Trapegeer site.

Localised flow patterns in the vicinity of, and on sandbanks, have been demonstrated by a number of authors studying tidal current interaction with headlands and their associated sandbanks (PATTIARATCHI & COLLINS (1987); YANG & RUDDICK (1997)). In general, current speeds in excess of about 0.4 m/s will have a significant effect on sediment transport (SOULSBY (1997)). An interesting indication of the spatial variability in the current meter data can be identified near the area of interaction between the Nieuwpoort Bank and Stroombank (Stations 05/74, 33/70 and 28/69, shown in Fig. 2.02) (Fig. 4.05). At location 05/74, a depth-averaged current of 0.98 m/s is derived; more to the east, at locations 33/70 and 28/69, only 0.76 m/s and 0.57 m/s is attained, respectively. The higher current velocities at the first location can be correlated with the *in-situ* coarser seabed sediments, which represent lag deposits. A proportion of the fine-grained sediments advected towards the Stroombank, on the flood tide, will be transported along the Westdiep swale; another part will be advected towards the Kleine Rede.

As the current velocities observed at location 28/69 are lower, the finer-grained sediments in suspension can be deposited under low-energy conditions. The velocity difference at both ends of the Stroombank can be explained in terms of flow separation around the end of the sandbank. The higher current velocities at the narrowing part of the Westdiep swale are probably the result of a funnelling effect. Comparing the velocity profiles of the three stations, clear differences exist in the way the flood and ebb maxima are established following slack water. The pattern observed at location 05/74 is similar to that at most of the current meter locations, meaning that the highest current velocity at flood is reached in 1 hr (up to a maximum of 2 hr) in relation to slack water. The minimum current velocity, during the successive ebbing phase of the tide, is reached some 4 hr later. Such a steep velocity profile is in contrast to the rounded profiles which are characteristic of the observations obtained for the locations 33/70 and 28/69 near the Stroombank. At the first location the velocity profile is even reversed, meaning that the flooding phase after slack water now lasts about 4 hr; this is followed by an ebb minimum some 2 hr later. This pattern implies that the current velocities, during the flood, remain high for 2 further hours; this indicates that more suspended load can be bypassed through the Westdiep swale. As will be demonstrated in the following chapters, this area plays an important role in the functioning of the coastal system under consideration.

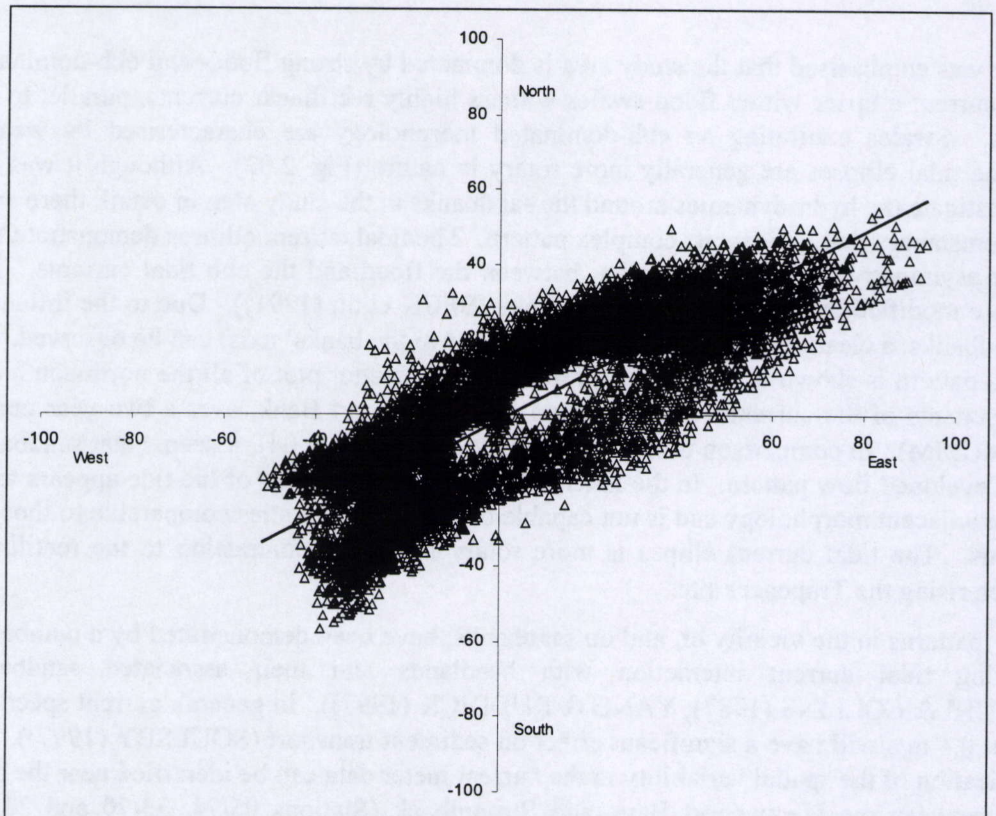


Figure 4.03 – Nieuwpoort Bank: scatter plot of all the north-south and west-east components of the velocity (cm/s) (Data source MUMM) (For station location, see Figure 2.02)

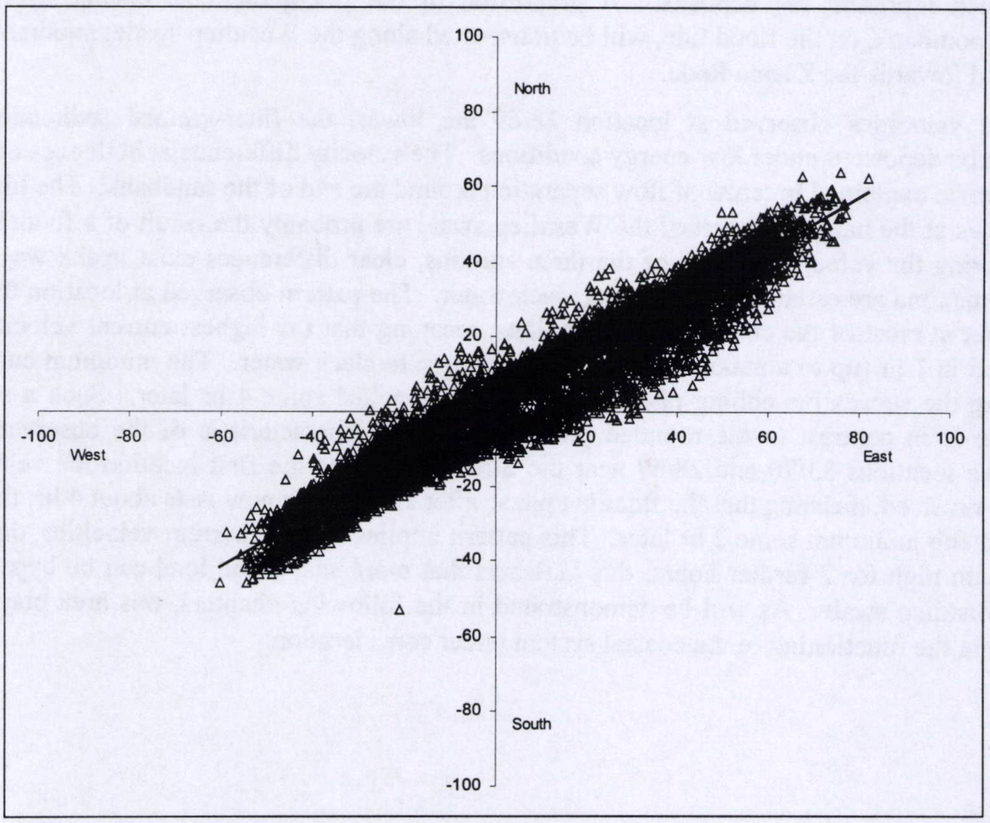


Figure 4.04 – Trapegeer site: scatter plot of all the north-south and west-east components of the velocity (cm/s) (Data source MUMM) (For station location, see Figure 2.02)

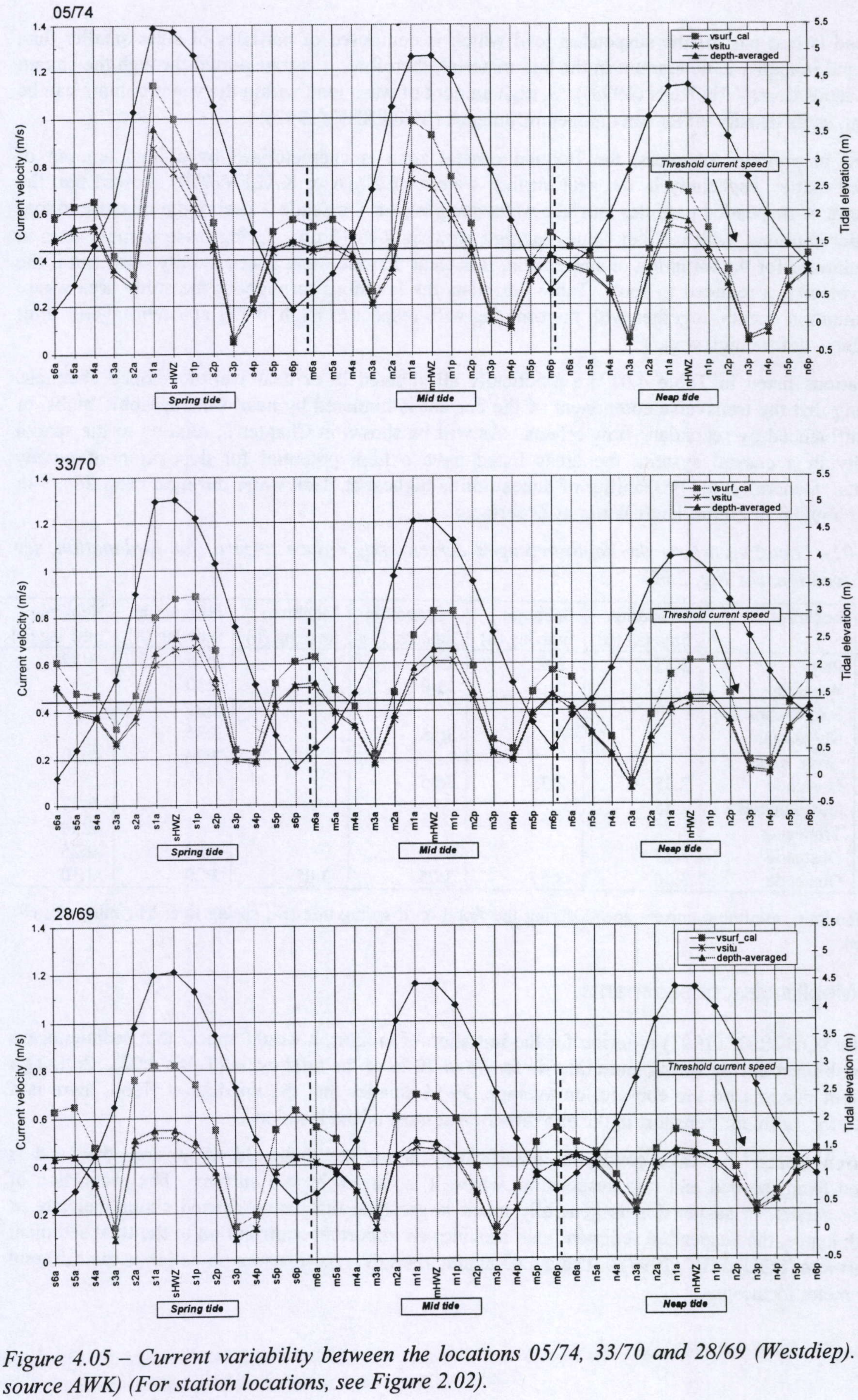


Figure 4.05 – Current variability between the locations 05/74, 33/70 and 28/69 (Westdiep). (Data source AWK) (For station locations, see Figure 2.02).

4.2.1. Wash load

Wash load is that part of the suspended load which is composed of particles of sizes smaller than those found in appreciable amount in the bed material; therefore, it is transported through the stream without deposition (VAN RIJN (1993)). A high amount of wash load within the water column can be important, as its density effect can dampen turbulence (SOULSBY (1997)).

As stated in previous chapters, the Belgian coastal zone is characterised by a high amount of suspended matter, especially in the near surface waters. EISMA & KALF (1979) showed that the size spectra of suspended particles (surface water samples) off Oostende – Zeebrugge lie close to log-normal distributions, with median values ranging between 7 to 10 µm. Using these particle sizes in the calculations for the initiation of suspension, it is clear that the wash load can only settle out if the current velocity is reduced to zero. Table 4.01 lists the locations throughout the study area where such a situation occurs, together with the time lag with respect to High Water at Zeebrugge (+ after high water; - before high water).

The locations listed in Table 4.01 are practically all situated in or near well-developed channels, suggesting that the transverse component of the current is hindered by nearby topographic highs, or can be influenced by secondary flow effects. As will be shown in Chapter 5, relating to the spatial variability in a coastal system, the areas listed have a high potential for deposition of muddy sediments. Generally, the probability of deposition is highest at slack water during a neap tide, 3 hr after and about 3 hr before High Water at Zeebrugge.

Table 4.01– Locations where the depth-averaged current may reduce to zero (for explanation, see text; for location, see Fig. 2.02)

Station	Location	Sfloodmin time lag (h)	Sebbmin time lag (h)	Mfloodmin time lag (h)	Mebbmin time lag (h)	Nfloodmin time lag (h)	Nebbmin time lag (h)
03/74	Potje	2:35	-2:55	2:30		2:15	-3:35
05/74	Westdiep			3:40		3:30	
06/74	Stroombank (E)					3:25	
08/74	Negenvaam			3:55		3:35	
01/75	Grote Rede					3:20	-2:10
09/82	Oostende	2:55	-2:35	3:05			
01/87	Oostduinkerke	2:45					-3:20
03/87	Trapegeer						-2:50
01/88	Oostende	3:25		3:25		3:40	-2:25
02/88	Oostende	3:00	-2:55	3:05	-3:05	3:20	-3:10

Key: Sfloodmin: minimum current speed during the flood on a spring tide (S-: spring tide, M-: mid tide, N-: neap tide).

4.2.2. Mobilisation of sediments

Using the SOULSBY (1997) criterion for the initiation of motion, it would appear that sediments are easily mobilised during spring and mid-tide for up to 70 % of the tidal cycle (Table 4.02). Although the current maxima on the ebb are, on average, 39 % smaller that the maxima at flood, there is a potential for sediment transport in the ebb direction at most of the locations.

For current speeds or wave conditions significantly above the threshold of motion, the sand is entrained from the bed and into suspension, where it is carried by the current. The proportion of sediment carried in suspension is generally much larger than that being carried simultaneously as bedload; hence, the suspended sediment load provides an important contribution to the total sediment transport rate (SOULSBY (1997)). Table 4.03 summarises the resuspension potential, at the different current meter locations.

Table 4.02– Initiation of motion (using SOULSBY (1997)*) at some of the current meter locations (for station location, see Fig. 2.02)*

				Spring tide		Mid tide		Neap tide	
Station	***Location***	***d50* (µm)**	***Uavcr* (m/s)**	***Flood* (%)**	***Ebb* (%)**	***Flood* (%)**	***Ebb* (%)**	***Flood* (%)**	***Ebb* (%)**
01/60	Grote Rede (WB)	210	0.43	31 (1a-2p)	31 (5p-5a)	31 (1a-2p)	23 (6p-5a)	31 (1a-2p)	23 (6p-5a)
03/61	Kleine Rede	188	0.44	31 (2a-1p)	31 (5p-5a)	31 (2a-1p)	**38** (5p-4a)	0	0
05/62	Westdiep	327	0.45	31 (2a-1p)	15 ((5a-4a)	23 (1a-1p)	15 (5a-4a)	0	23 (6p-5a)
15/65	Ravelingen	233	0.45	31 (1a-2p)	23 (6p-3a)	31 (1a-2p)	23 (6a-4a)	0	8 (5a)
18/66	Outer Nieuwpoort Bank	255	0.47	23 (1a-1p)	31 (6p-4a)	23 (1a-1p)	15 (6a-5a)	0	0
19/67	Westdiep	210	0.47	**38** (2a-2p)	31 (6p-4a)	31 (2a-1p)	31 (6p-4a)	23 (1a-1p)	0
20/67	Noordpas	210	0.45	23 (2a-1p)	31 (5p-4a)	15 (1a-HW)	31 (6p-4a)	15 (1a-HW)	0
28/69	Westdiep	114	0.44	31 (2a-1p)	8 (5a)	15 (1a-HW)	0	8 (1a)	8 (6a)
31/70	Grote Rede	17	0.36	31 (2a-2p)	23 (6p-5a)	23 (1a-1p)	15 (6a-5a)	0	0
33/70	Noordoostpas*	195	0.45	31 (1a-2p)	15 (6p-6a)	31 (1a-2p)	15 (6p-6a)	0	0
36/71	Near Oostende	205	0.42	15 (1a-HW)	0	23 (1a-1p)	0	8 (1a)	0
02/74	Trapegeer	204	0.43	23 (2a-HW)	15 (5a-4a)	15 (1a-HW)	0	8 (1a)	0
03/74	Potje	179	0.42	23 (2a-HW)	0	23 (2a-HW)	0	15 (2a-1a)	0
05/74	WK70 Westdiep	210	0.45	31 (1a-2p)	**38** (5p-4a)	23 (1a-1p)	15 (6a-5a)	15 (1a-HW)	0
06/74	Inner Stroombank	188	0.42	23 (1a-1p)	0	23 (1a-1p)	0	8 HW)	0
07/74	Oostende Bank, West	244	0.44	23 (1a-1p)	15 (5a-4a)	23 (1a-1p)	15 (5a-4a)	0	0
08/74	Negenvaam (MB)	244	0.49	**38** (2a-2p)	31 (6p-4a)	23 (1a-1p)	31 (6p-4a)	0	0
01/75	Outer Stroombank	200	0.44	23 (1a-1p)	31 (5p-4a)	23 (1a-1p)	31 (6p-4a)	23 (1a-1p)	15 (5a-4a)
09/82	WK57 near Oostende	205	0.42	15 (1a-HW)	0	23 (1a-1p)	0	15 (1a-HW)	0
01/87	WK3 Oostduinkerke	194	0.44	15 (1a-HW)	31 (5p-5a)	31 (2a-HW)	31 (5p-6a)	8 (1a)	0
02/87	Stroombank, West	196	0.44	31 (2a-1p)	0	31 (2a-1p)	0	0	0
03/87	Trapegeer	204	0.44	23 (1a-1p)	**38** (5p-4a)	23 (1a-1p)	**38** (5p-4a)	15 (1a-HW)	31 (5p-5a)
07/87	Smalbank	210	0.42	31 (2a-1p)	0	23 (2a-HW)	0	23 (2a-HW)	0
01/88	Near Oostende E	205	0.42	31 (1a-2p)	0	31 (1a-2p)	0	23 (1a-1p)	0
02/88	Near Oostende W	205	0.42	31 (2a-1p)	0	31 (2a-1p)	0	31 (2a-1p)	0

Key: Uavcr is the depth-averaged critical velocity, calculated according to SOULSBY (1997); it is here averaged over spring, mid and neap tides as the value is dependant upon the depth differences at each hour of the tidal cycle. The particle diameter (d50 µm) is extracted from the sedimentological data base, together with external information. The percentages of mobility refer to the time during which the average bed shear velocity exceeds the threshold value; they are supplemented by the time over which the sediments can be resuspended (1a-1p: from 1 hr before (a) high water at Zeebrugge up to 1 hr after (p) high water). (WB): Wenduine Bank; Noordoostpas: interaction zone of the Nieuwpoort Bank and the Stroombank (Westdiep).

Table 4.03– Resuspension potential at some of the current meter locations (using the VAN RIJN (1993) *criterion of the initiation of suspension). (For location, see Fig. 2.02).*

				Spring tide		**Mid tide**		**Neap tide**	
Station	***Location***	***d50*** (μm)	***Uavcrs*** (m/s)	***Flood*** (%)	***Ebb*** (%)	***Flood*** (%)	***Ebb*** (%)	***Flood*** (%)	***Ebb*** (%)
01/60	Grote Rede (WB)	210	0.58	23 (1a-1p)	0	23 (1a-1p)	0	15 (1a-HW)	0
03/61	Kleine Rede	188	0.55	23 (1a-1p)	0	23 (1a-1p)	8 (6a)	0	0
05/62	Westdiep	327	0.69	15 (1a-HW)	0	0	0	0	0
15/65	Ravelingen	233	0.64	15 (1a-HW)	8 (4a)	0	0	0	0
18/66	Outer Nieuwpoort Bank	255	0.68	15 (1a-HW)	0	0	0	0	0
19/67	Westdiep	210	0.61	23 (1a-1p)	15 (5a-4a)	23 (1a-1p)	0	0	0
20/67	Noordpas	210	0.59	8 (1a)	8 (5a)	8 (1a)	0	0	0
28/69	Westdiep	114	0.37	31 (2a-1p)	23 (6p-5a)	31 (2a-1p)	23 (6p-5a)	31 (2a-1p)	23 (6p-5a)
31/70	Grote Rede	17	0	46 (3a-3p)	54 (4p-4a)	46 (3a-3p)	54 (4p-4a)	46 (3a-3p)	54 (4p-4a)
33/70	Noordoost Pas*	195	0.57	23 (1a-1p)	0	15 (HW-1p)	0	0	0
36/71	Near Oostende	205	0.57	8 (1a)	0	15 (1a-HW)	0	0	0
02/74	Trapegeer	204	0.59	8 (1a)	0	0	0	0	0
03/74	Potje	179	0.53	15 (2a-1a)	0	15 (2a-1a)	0	8 (2a)	0
05/74	WK70 Westdiep	210	0.59	23 (1a-1p)	0	23 (1a-1p)	0	0	0
06/74	Inner Stroombank	188	0.54	23 (1a-1p)	0	15 (1a-HW)	0	0	0
07/74	Oostende Bank, West	244	0.65	0	0	0	0	0	0
08/74	Negenvaam (MB)	244	0.69	23 (1a-1p)	8 (5a)	15 (1a-HW)	0	0	0
01/75	Outer Stroombank	200	0.58	15 (1a-HW)	8 (5a)	15 (1a-HW)	8 (5a)	8 (1a)	0
09/82	WK57 near Oostende	205	0.57	8 (1a)	0	15 (1a-HW)	0	8 (1a)	0
01/87	WK3 Oostduinkerke	194	0.58	15 (1a-HW)	0	8 (1a)	0	0	0
02/87	Stroombank, West	196	0.58	15 (1a-HW)	0	15 (1a-HW)	0	0	0
03/87	Trapegeer	204	0.59	15 (1a-HW)	8 (5a)	15 (1a-HW)	8 (5a)	0	0
07/87	Smalbank	210	0.57	23 (2a-HW)	0	15 (1a-HW)	0	0	0
01/88	Near Oostende E	205	0.57	23 (1a-1p)	0	23 (1a-1p)	0	23 (1a-1p)	0
02/88	Near Oostende W	205	0.57	15 (1a-HW)	0	15 (1a-HW)	0	15 (1a-HW)	0

Key: Uavcrs is the average critical velocity, at the initiation of suspension; it is here averaged over spring, mid and neap tides, as the value is dependant upon the depth differences at each hour of the tidal cycle. The particle diameter (d50 μm) is extracted from the sedimentological data base together with external information. The percentages of mobility refer to the time during which the average bed shear velocity exceeds the threshold value; they are supplemented by the time over which the sediments can be resuspended (1a-1p: from 1 hr before (a) high water at Zeebrugge up to 1 hr after (p) high water). (WB): Wenduine Bank; Noordoostpas: interaction zone of the Nieuwpoort Bank and the Stroombank (Westdiep).

Following the VAN RIJN (1993) criterion for initiation of suspension, it may be seen that sediments can be brought into the water column during spring and mid-tides corresponding (mostly) to a time span of 1 hr before and up to 1 hr after high water. On a neap tide hardly any sediment can be resuspended, except for areas having a particular bathymetric configuration e.g. leading to acceleration of the currents. The current meter locations where the sediments can be resuspended during the ebb, are situated in the major swales along the western boundary of the study area. This distortion may indicate, that during the ebbing phase of the tide, the water flow is funnelled along those channels. The potential of resuspension during the ebb, at location 01/75 in the shallower regions of the Grote Rede swale may confirm its ebb-domination; this could mean that, on some occasions, an important sediment flux in a southwestern direction can be generated.

The coarser surficial sediments in the vicinity of the major sandbanks are unlikely to be resuspended by the average currents.

4.2.3. Transport capacity of the flow

In the previous paragraph, some discussion was presented on the critical depth-averaged current velocity for the resuspension of *in-situ* sediments. Another important issue is to identify the range of sediment sizes that can be transported by the flow. In order to enhance the link with the following chapters, the threshold of motion calculations were repeated for each phi quarter, ranging from 2.50 ϕ up to 1.25 ϕ (177 μm - 420 μm).

Under currents alone, the calculations (Table 4.04) show that sediments having a median size of 177 μm can be transported throughout the area. Only around station 28/69, to the southwest of the Stroombank (Fig. 2.02), the flow is insufficient to transport sediments having a d50 value of 210 μm. A grain-size of 250 μm can only be advected where flow funnelling effects are to be expected in the well-developed flood swales. These stations are those where also grains up to 420 μm (d50) can be transported. It should be emphasised that these results represent a minimum competence, since the combined action of currents and waves non-linearly enhances sediment transport. However, on the basis of the derived information, it would seem likely that the source area for the coarser sediments lies to the west. Only the more offshore areas (e.g. swale to the north of the Ravelingen (15/65), the western part of the Oostende Bank (07/74), the Negenvaam swale (08/74)) are associated with a maximum competence of the ebb current to transport grains of up to 420 μm. Closer to the coast, grains in excess of 250 μm can only be transported along the Trapegeer (03/87) and along the western part of the Westdiep swale (19/67) (Fig. 2.02).

4.2.4. Prediction of sand transport rates

The current meter data were used also to predict bedload sediment transport directions, together with some indications of the rate of transport. Here, only the influence of currents is considered. The "total sediment transport rate" is the quantity required most commonly, for addressing practical applications such as: the infill of dredged channels; the dispersion of soil-heaps; and the morphodynamic response of coastal areas to engineering works (SOULSBY (1997)). Table 4.05 lists the rates of sand transport, as both bedload and total load. Figure 4.06 represents both rates, relative to one other.

Bedload transport can occur: over a flat bed at *low* flows; in conjunction with ripples or larger bedforms, for *stronger* flows; or over a flat bed for *very strong* flows where the ripples are washed out (sheet flow). The response time of a sand grain in bedload motion is, however, very short when compared to a tidal period or a wave period (SOULSBY (1997)).

Table 4.04 - Transport capacity of the flow, throughout the area under the influence of currents alone. (For location, see Fig. 2.02).

		2.50 ϕ ~ 177 μm		2.25 ϕ ~ 210 μm		2.00 ϕ ~ 250 μm		1.75 ϕ ~ 297 μm		1.50 ϕ ~ 354 μm		1.25 ϕ ~ 420 μm	
Station	***Location***	***Flood*** S-M-N (%)	***Ebb*** **S-M-N (%)**	***Flood*** S-M-N (%)	***Ebb*** **S-M-N (%)**	***Flood*** S-M-N (%)	***Ebb*** **S-M-N (%)**	***Flood*** S-M-N (%)	***Ebb*** **S-M-N (%)**	***Flood*** S-M-N (%)	***Ebb*** **S-M-N (%)**	***Flood*** S-M-N (%)	***Ebb*** **S-M-N (%)**
01/60	Grote Rede (WB)	23-23-23	0-0-0	**23**-23-15	0-0-0	**23**-23-8	0-0-0	**23**-23-M	0-0-0	**23**-15-0	0-0-0	**23**-15-0	0-0-0
03/61	Kleine Rede	23-23-0	0-15-0	15-15-0	0-0-0	15-15-0	0-0-0	15-15-0	0-M-0	15-8-0	0-0-0	15-8-0	0-0-0
05/62	Westdiep	23-23-0	8-M-0	15-15-0	M-0-0	15-M-0	0-0-0	15-0-0	0-M-0	15-0-0	0-0-0	15-0-0	0-0-0
15/65	Ravelingen	**31**-23-0	15-15-0	**23**-8-0	15-8-0	15-M-0	8-0-0	M-M-0	M-M-0	M-0-0	**M**-0-0	M-0-0	M-0-0
18/66	Outer Nieuwpoort Bank	23-8-0	8-0-0	**23**-8-0	M-0-0	15-0-0	0-0-0	8-0-0	0-0-0	8-0-0	0-0-0	8-0-0	0-0-0
19/67	Westdiep	**31**-23-M	23-M-0	**23**-23-M	15-0-0	**23**-15-0	**15**-0-0	**23**-15-M	M-M-0	**23**-15-0	**M**-0-0	**23**-15-0	0-0-0
20/67	Noordpas	8-8-0	15-8-0	8-8-0	8-M-0	M-0-0	0-0-0	0-0-0	0-M-0	0-0-0	0-0-0	0-0-0	0-0-0
28/69	Westdiep	15-0-0	0-0-0	0-0-0	0-0-0	0-0-0	0-0-0	0-0-0	0-0-0	0-0-0	0-0-0	0-0-0	0-0-0
31/70	Grote Rede	23-15-0	0-0-0	8-8-0	0-0-0	M-0-0	0-0-0	M-0-0	0-0-0	M-0-0	0-0-0	M-0-0	0-0-0
33/70	Noordoost Pas*	23-23-0	M-M-0	**23**-15-0	0-0-0	15-15-0	0-0-0	15-M-0	0-M-0	8-0-0	0-0-0	8-0-0	0-0-0
36/71	Near Oostende	15-15-0	0-0-0	8-15-0	0-0-0	8-8-0	0-0-0	8-8-0	0-0-0	8-8-0	0-0-0	8-8-0	0-0-0
02/74	Trapegeer	15-8-0	8-0-0	8-M-0	0-0-0	8-0-0	0-0-0	M-0-0	0-0-0	M-0-0	0-0-0	M-0-0	0-0-0
03/74	Potje	23-15-8	0-0-0	15-15-M	0-0-0	15-M-0	0-0-0	8-M-M	0-0-0	8-0-0	0-0-0	8-0-0	0-0-0
05/74	WK70 Westdiep	23-23-15	15-0-0	**23**-23-0	0-0-0	**23**-15-0	0-0-0	15-15-M	0-0-0	15-15-0	0-0-0	15-15-0	0-0-0
06/74	Inner Stroombank	23-23-0	0-0-0	**23**-15-0	0-0-0	15-8-0	0-0-0	15-8-0	0-0-0	15-M-0	0-0-0	15-M-0	0-0-0
07/74	Oostende Bank, West	15-8-0	15-0-0	15-M-0	8-0-0	M-0-0	M-0-0	M-0-0	0-0-0	0-0-0	0-0-0	0-0-0	0-0-0
08/74	Negenvaam (MB)	23-23-0	**31**-23-0	**23**-23-0	**23**-8-0	**23**-15-0	8-0-0	15-15-0	**8**-M-0	15-8-0	8-0-0	15-8-0	**8**-0-0
01/75	Outer Stroombank	15-15-15	15-8-8	15-15-8	8-8-M	8-8-M	M-0-0	8-0-M	0-M-0	8-0-0	0-0-0	8-0-0	0-0-0
09/82	WK57 near Oostende	15-15-8	0-0-0	15-15-8	0-0-0	8-8-M	0-0-0	8-8-M	0-0-0	8-8-0	0-0-0	8-8-0	0-0-0
01/87	WK3 Oostduinkerke	15-15-0	M-0-0	15-8-0	0-0-0	8-8-0	0-0-0	8-8-0	0-0-0	8-M-0	0-0-0	8-M-0	0-0-0
02/87	Stroombank, West	23-15-0	0-0-0	15-15-0	0-0-0	15-8-0	0-0-0	M-M-0	0-0-0	M-M-0	0-0-0	M-0-0	0-0-0
03/87	Trapegeer	15-15-15	23-23-8	15-15-M	15-8-M	15-8-M	8-8-0	8-8-M	M-M-0	8-8-0	0-0-0	8-8-0	0-0-0
07/87	Smalbank	**31**-23-0	0-0-0	**23**-15-0	0-0-0	15-M-0	0-0-0	15-0-0	0-0-0	15-0-0	0-0-0	15-0-0	0-0-0
01/88	Near Oostende E	23-23-23	0-0-0	**23**-23-23	0-0-0	**23**-15-15	0-0-0	15-15-15	0-0-0	15-15-15	0-0-0	15-15-15	0-0-0
02/88	Near Oostende W	15-15-15	0-0-0	15-15-15	0-0-0	15-8-M	0-0-0	15-8-M	0-0-0	8-M-0	0-0-0	8-M-0	0-0-0

Key: S-: Spring tide, M-: Mid tide, N-: Neap tide. M is indicated when only flood or ebb maxima are able to transport sediment of the indicated range. The critical depth-averaged velocity for the initiation of suspension for the given grain-sizes, is calculated according to VAN RIJN (1993). (WB): Wenduine Bank; Noordoostpas: interaction zone of the Nieuwpoort Bank and the Stroombank (Westdiep).

Table 4.05– Mean bedload and total load transport rates under currents alone (For location, see Fig. 2.02).

station	Location	h (m)	d50 (µm)	d90 (µm)	qb*10^{-6} (m^2/s)	qb (°)	qtvr*10^{-6} (m^2/s)	qtvr(°)	qteh*10^{-6} (m^2/s)	qteh (°)
01/60	Grote Rede (WB)	-8	210	463	53	49	758	49	556	49
03/61	Kleine Rede	-8	188	332	17	53	305	53	219	53
05/62	Westdiep	-10	327	718	16	58	114	55	103	54
15/65	Ravelingen	-11	233	353	4	67	49	62	55	64
18/66	Outer Nieuwpoort Bank	-15	255	419	11	68	97	66	101	66
19/67	Westdiep	-17	210	463	32	53	675	53	396	53
20/67	Noordpas	-11	210	463	1	172	15	79	8	152
28/69	Westdiep	-9	114	276	3	72	22	74	63	72
31/70	Grote Rede	-11	17	186	0	71	52	72	154	71
33/70	Noordoost Pas*	-11	195	404	15	58	169	59	166	58
36/71	Near Oostende	-6	205	343	29	45	407	44	297	45
02/74	Trapegeer	-7	204	282	6	65	32	65	54	65
03/74	Potje	-6	179	254	15	62	101	62	156	62
05/74	WK70 Westdiep	-11	210	463	35	61	560	62	387	61
06/74	Inner Stroombank	-9	188	332	18	50	225	50	224	50
07/74	Oostende Bank, West	-9	244	347	4	92	20	79	27	89
08/74	Negenvaam (MB)	-21	244	347	16	64	331	60	203	63
01/75	Outer Stroombank	-9	200	295	9	85	99	79	102	82
09/82	WK57 near Oostende	-5	205	343	23	59	228	59	220	59
01/87	WK3 Oostduinkerke	-10	194	293	10	35	97	52	103	38
02/87	Stroombank, West	-9	196	308	29	65	86	65	120	64
03/87	Trapegeer	-9	204	282	2	14	106	50	43	38
07/87	Smalbank	-6	210	463	16	64	118	67	143	65
01/88	Near Oostende E	-6	205	343	58	61	691	61	570	61
02/88	Near Oostende W	-6	205	343	22	53	159	54	200	53

Key: *h-*: depth mllws; *qb-*: bedload transport rate calculated according to NIELSEN (1992); *qtvr-*: total load transport rate, according to VAN RIJN (1993); *qteh-*: total load transport rate, according to the ENGELUND & HANSEN (1972) equation. (WB): Wenduine Bank; Noordoostpas: interaction zone of the Nieuwpoort Bank and the Stroombank (Westdiep).

The ratio of bedload transport and the derived rate according to NIELSEN (1992) compared with the total load transport rate according to ENGELUND & HANSEN (1972) varies between 0 at Station 31/70 (Grote Rede), to a maximum of 24 % at Station 02/87 (near the western end of the Stroombank). The bedload and total load transport rate vectors are both represented in Figure 4.07. Residual forces clearly drive sediment in a northeastern direction, as was expected from the flood-dominant flow over the area (Fig. 2.02, Section 2.2). The transport vectors are aligned with the bathymetry in the flood-dominated swales. All the locations on or near the sandbanks exhibit, however, a veering towards the bank; this can be seen near the Middelkerke Bank, Oostende Bank, Smalbank, Nieuwpoort Bank, Stroombank and Wenduine Bank. Remarkably, the transport vectors tend to be offshore-orientated along the western part of the study area; they are more shorewards to the east.

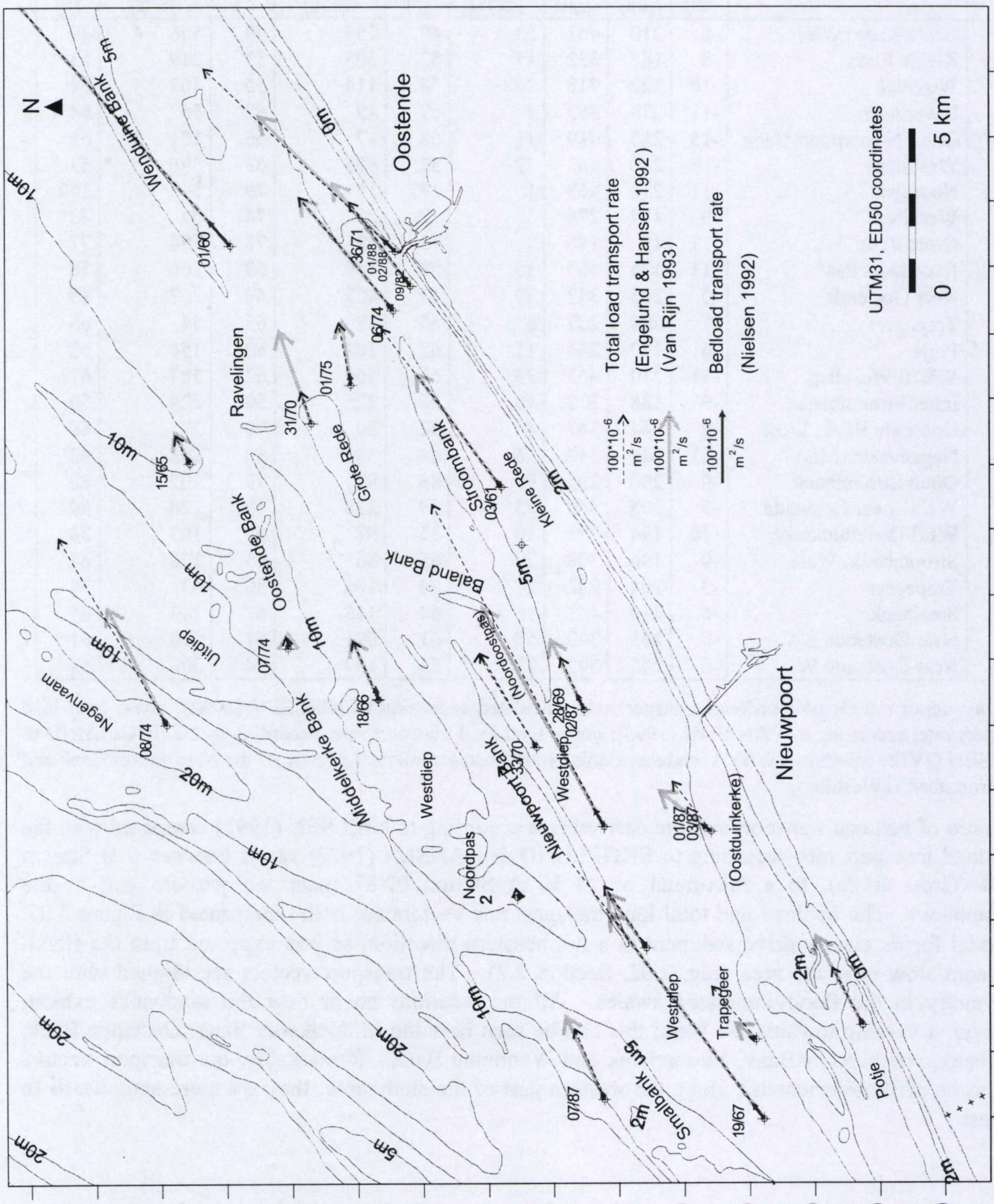


Figure 4.06 - The total load and bedload transport rate vectors, calculated for the influence of tidal currents alone.

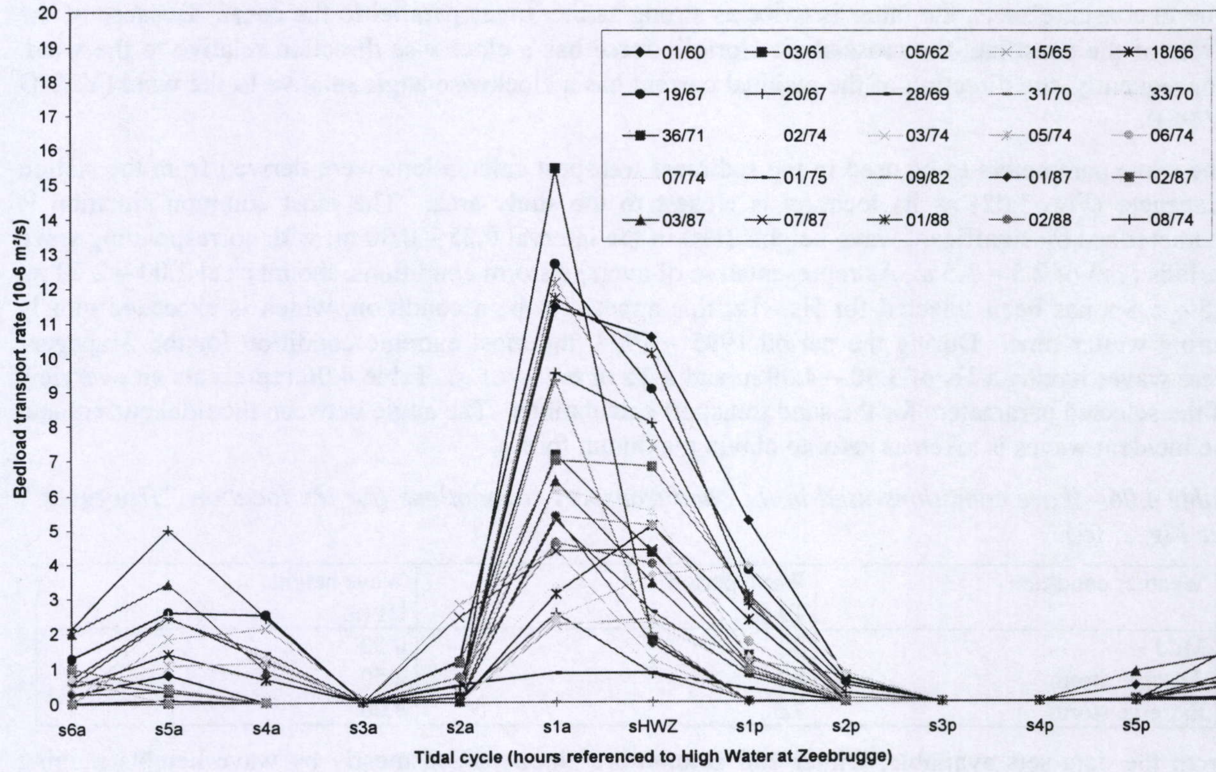


Figure 4.07 - Variation of bedload transport rate during the tidal cycle at spring tide (according to NIELSEN (1992)) (for station location, see Fig. 2.02).

On the basis of the results presented in Figure 4.07, it is clear that the bedload transport rate is highest 1 hr before High Water at Zeebrugge. Three hours before and after high water, the flow is incapable of moving the sediments. The ebbing phase of the tide is, in general, far less competent to initiate the bedload movement.

4.3. Sediment transport under the combined action of currents and waves

In most areas of coastal and shelf seas, both waves and currents play important roles in the prevailing sediment dynamics. Both interact hydrodynamically with each other, so that their combined behaviour is not a linear sum of their separate behaviours (SOULSBY (1997)). In the shallow marine environment, the effect of wave-induced currents, combined with tidal flow, becomes more important (GRANT & MADSEN (1979) and HALLERMEIER (1981)).

Currents stir up and transport sediments, but the direction of net long-term sediment transport may be very different from the residual current direction, mainly due to the non-linearity of sediment transport and current speed and the effect of wave-stirring (GAO & COLLINS (1997)). Moreover, waves also give rise to steady current motions such as longshore currents, undertow, and mass-transport (or streaming) velocities which transport sediment. The asymmetry of velocities beneath the crest and trough of waves is another source of net transport of sediments tending to drive sediment in the direction of wave travel.

VERLAAN & GROENENDIJK (1993) identified that wind effects are controlling residual currents along the Belgian and Dutch coasts, increasing in importance with decreasing depths. VAN DEN EYNDE (1995) showed the dependency of residual currents to wind velocities and directions along the Belgian continental shelf. YANG (1998) further developed this hypothesis and concluded that the residual forces are related linearly to wind strength. A relationship is derived between wind stresses and the slope of the water surface. Apparently, a high slope is reached when winds blow from an ESE direction, parallel to the coast, and for WNW directions. The water surface slope is at a maximum for winds blowing perpendicular to the coast, i.e. for eastern and western winds.

Due to coastal effects, the latter is twice as strong as the forces parallel to the coast. Because of the effect of the coastline, the cross-shore Coriolis force has a clockwise direction relative to the wind. Consequently, the direction of the residual current has a clockwise angle relative to the wind (YANG (1998)).

The wave parameters to be used in the sediment transport calculations were derived from the station Trapegeer (Fig. 2.02) as its location is closest to the study area. The most common situation is characterised by significant wave heights (Hs) in the interval 0.25 – 0.50 m, with corresponding wave periods (Tz) of 2.5 – 3.5 s. As representative of average storm conditions, the interval 2.00 – 2.50 m, 4.5 – 5.5 s has been selected for Hs –Tz; this appears to be a condition, which is exceeded mostly during winter time. During the period 1995 – 1998, the most extreme condition for the Trapegeer were waves having a Hs of 3.50 – 4.00 m and a Tz of 6.5 – 7.5 s. Table 4.06 represents an overview of the selected parameters for the sand transport calculations. The angle between the tidal current and the incident waves is taken as zero, to obtain maximum forces.

Table 4.06– Wave conditions used in the sand transport calculations (for the location "Trapegeer", see Fig. 2. 02).

Weather condition	Wave period Tz (s)	Wave height Hs (m)
Mild	3.5	0.50
Average storm	5.5	2.50
Extreme storm	7.5	4.00

From the data sets available, winter and autumn are characterised mostly by wave heights ranging from 0.50 to 1 m, with corresponding periods of 3.5 – 4.5 s; whilst spring and summer mostly have significant wave heights of 0.25 – 0.5 m and periods of 2.5 – 3.5 s.

Plotting the depth-averaged velocity against the total load sediment transport for the different wave conditions, shows that the amplification of sediment transport is greatest when the depth-averaged velocity is low; it becomes progressively smaller for higher current speeds (Fig. 4.08). This pattern implies that, in general, the weaker ebb-currents can be enhanced strongly by waves from a northeasterly direction; this means that during the ebbing phase of the tidal cycle, they can become competent to reverse the asymmetry of bedforms. The following flood tide will not always be able to counteract this effect. It may be noted that under mild conditions, sediment transport only becomes important at depth-averaged currents of more than 0.4 m/s. The ratio between bedload and the total load sediment transport rate varied around 10 % for the different wave conditions.

The results presented in Figure 4.08 have been obtained using the "total load" Soulsby-Van Rijn formula; this takes only into account the root-mean-square wave orbital velocity, regardless of the incident wave angle (Section 4.4.3).

To estimate the effect of the wave direction on sediment transport, a specific condition was selected, which could be correlated with field observations undertaken in September 1996. This campaign was preceded (18-22/09/1996) by a persistent northeasterly wind, giving rise to waves having an incident angle of N70°E (range 45-90°), a significant wave height of 1.8 m and an approximate zero-crossing period of 5 s.

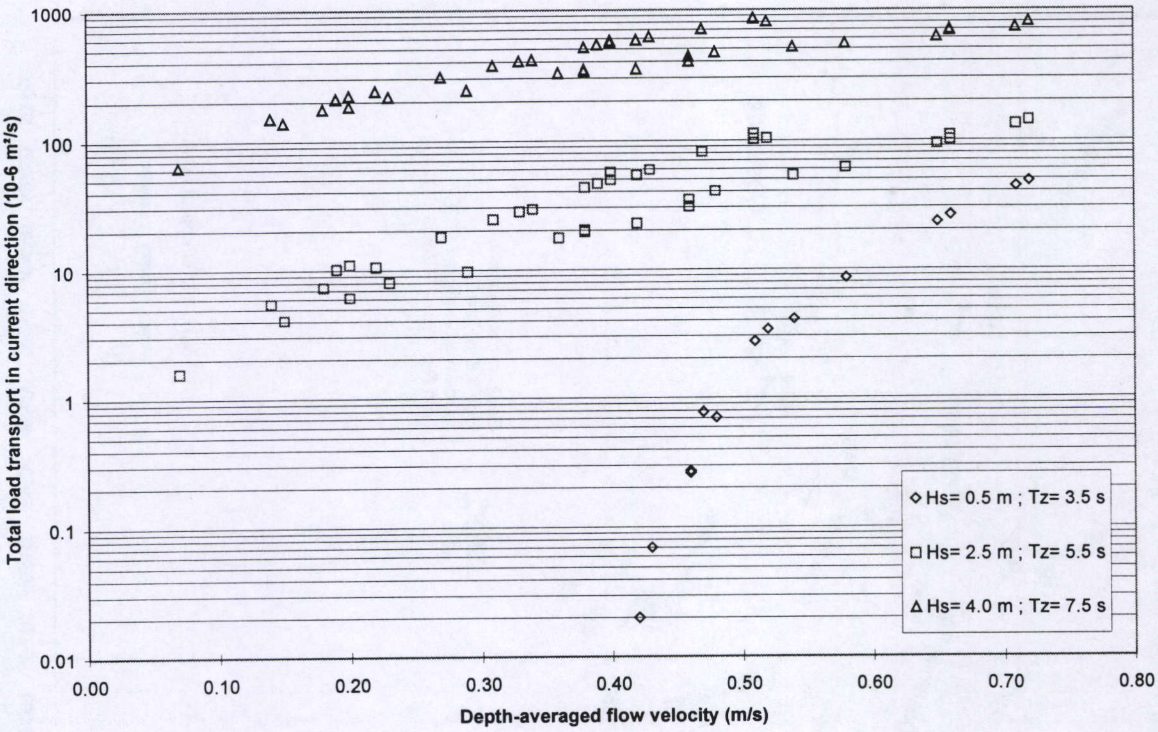


Figure 4.08 - Total load sediment transport (qt) calculated according to the Soulsby – Van Rijn formula as a function of the depth-averaged current velocity. Qt-values of Station 33/70 (Fig. 2.02), over a spring, mid- and neap-tidal cycle were used in the presentation.

The mean bedload transport rate has been calculated according to Van Rijn's TRANSPOR programme, taking into account the angle between the current and the incident wave (Section 3.4.3). Figure 4.09 shows the results integrated over a mid-tide cycle, as the campaign took place during a neap tide and the weather conditions preceding the campaign were persistent over 5 days. As might be anticipated from Figure 4.08, the lower velocity components are enhanced mainly by higher energy events. Although the maximum current velocities at flood are still dominant, the ebb components of the tide are reinforced; this leads to a residual bedload transport pattern in a southwesterly direction. The locations where the flood currents are very strong (i.e. 18/66, 19/67, 31/70, 08/74) are approximately equalled by the ebb currents, leading to a zero residual effect. These stations are associated with higher water depths, implying that waves are not fully capable to interact with the seabed. The ratio between bedload and total load transport rates ranges up to 56 % in the ebb direction; it is 46 %, on average, in the flood direction. During mild conditions, most sediment (90 %) is transported as suspension around high water. Sediment transport due to wave asymmetry is neglected. It may be noted that the veering of the current near topographic highs is minimized. The transport rate vectors along the western part of the study area are smaller than those located more to the east; this indicates that sediment is deposited along the transport pathway.

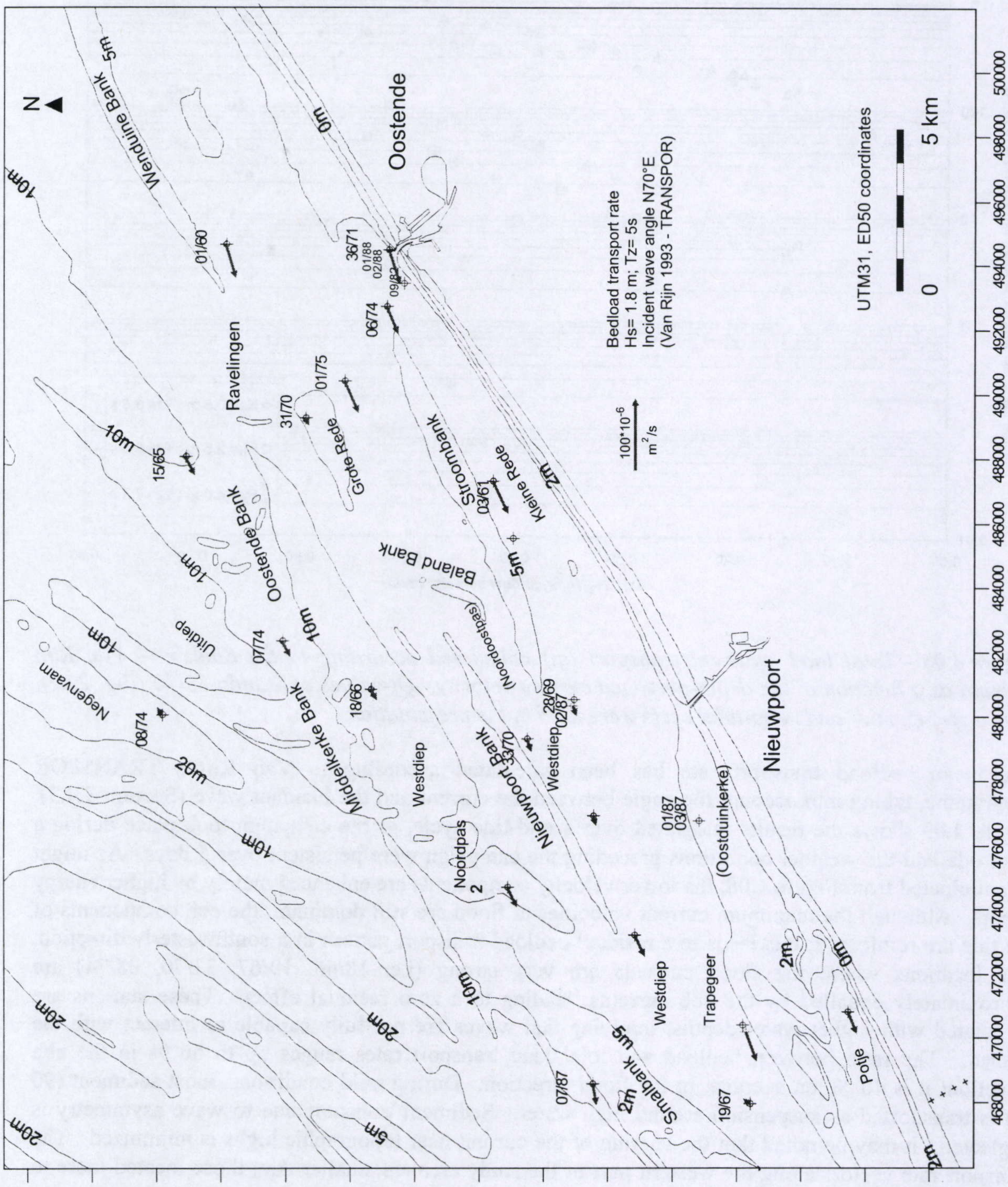


Figure 4.09 - The bedload transport rate vectors calculated for the combined action of currents and waves.

4.4. Conclusions

Sediment transport calculations, based upon current meter data permit the presentation of a regional description of sediment movement in the study area. It is clear from the results obtained that the physical functioning of the coastal system is influenced largely by strong flood- and ebb-dominated swales. Generally, the tidal velocities seem to be lower over the sandbanks, in the nearshore and where the swales are wider or cutting the sandbanks under a significant angle. Still, along the sandbanks, secondary effects may largely enhance sediment transport (PATTIARATCHI & COLLINS (1987)). The results confirm a residual movement of sediment in a northeasterly direction. The bed is especially mobile around high water at spring tide, but sediment transport can also take place during mid- and neap tides. Given the nature of the seabed and the strength of the flow, most of the sediment is carried in suspension; this means that only a small fraction is transported as bedload. Grains up to 210 μm are easily transported throughout the area, whilst grains coarser than 250 μm can only be transported in swales witnessing a funnelling effect of the current. Especially in the Westdiep swale (south of the Nieuwpoort Bank), currents are even strong enough to resuspend and transport coarser sediment. The fact that the current is highly rectilinear and strong means that a considerable amount of sediment can be advected along that swale, which can act as a source of material for the sandbanks. If both currents and waves are reinforced, sheet flow conditions can be encountered. Flow separation can be distinguished at the interaction zone of the Nieuwpoort Bank and Stroombank. Although this process leads, at first, to a weaking of the current, an acceleration of the current is suspected in the swale separating both of the sandbanks.

Generally, near the sandbanks, veering in the current can be observed. Moreover, the currents are somewhat weaker than in the swales; this leads to deposition of sediment and an increase in the bedload transport. The *in-situ* sediments are mostly coarser and are unlikely to be resuspended by the average currents. Still, the shallowness of the sandbanks implies a high vulnerability to wave activity. Thus, the wave bed shear stress might become dominant and introduce sheet flow conditions. This situation is especially the case when the banks are formed of finer-grained sediments.

Under currents alone, the flood is largely dominant over the ebb. However, bedload transport in a southwesterly direction can be initiated, especially in the swales witnessing an ebb-dominated morphology. Even moderate weather conditions from an easterly direction can reverse the residual transport direction. Due to the decreasing effect of waves with depth, the transport rates are highest in the shallower water regions. Moreover, in the flood-dominated swales, the flood component is still competent to counteract the ebb residual sediment movement. From the spatial variability of the transport rates, it seems that the amount is larger along the eastern part of the study area; this possibly indicates deposition of sediment along its pathway.

The effect of storms is difficult to calculate on the basis of the available data. Due to the non-linearity of sediment transport in relation to the current strength, the directions and magnitudes of transport rates are far from predictable. It is suspected that on some occassions large amounts of sediment could be resuspended and funnelled throughout the swales. The sediment is likely deposited where the current is hindered by topographic highs, such as sandbanks.

5. RESULTS: SPATIAL VARIABILITY OF A COASTAL SYSTEM

5.1. Introduction

Investigating the sediment- and morphodynamics of a near coastal area involves the study of a set of variables and their evaluation in time. The combination of both spatially varied flow (different flow paths for flood and ebb) and temporally varied flow (tide variations versus external controls) makes this area an interesting study object. However, before unravelling the temporal variations in a coastal system, it is of utmost importance to clearly differentiate between sub-environments, as these often hold the key for the localisation of likely sinks and sources. The scope of the present chapter can be summarised, stating VAN DE MEENE (1994): *"the recognition of small-scale bedforms, the sedimentary structures they produce, and the subsequent hydrodynamic interpretation of these deposits provide an idea of the processes that may dominate the present reworking of the sea bed, including the spatial variability related to the presence of the sandbanks*". Moreover, knowledge on the geometry of bedforms and the flow pattern around them is of great significance for hydraulic engineers and oceanographers who wish to understand sediment transport mechanisms and flow resistance (TANAKA & DANG (1996)).

Although a hypothesis on the genesis of the banks will be discussed in the following chapter, it can already be put forward that their generation, evolution and stability is likely a result of a rising sea-level and coastal retreat (DYER & HUNTLEY (in press)). Essential elements in the formation of sandbanks are, indeed, the availability of sand, and the strength of the currents to transport sediments. The mobile sediment can be either derived from the local seabed or from coastal erosion. Insight in the present-day sediment- and morphodynamics may hence provide information on the processes responsible for the up-building of the sandbanks. Sedimentary structures may form the link between processes on the event scale and processes/responses on the geological time scale (VAN DE MEENE (1994)). Still, even if they are of a relict origin, the hydrodynamic agents, currents and waves remain the driving forces in the maintenance mechanism of sandbanks. For a review of the formation, evolution and maintenance of sandbanks, reference is made to PATTIARATCHI & COLLINS (1987), HOUTHUYS (1990), VAN DE MEENE (1994) and DYER & HUNTLEY (in press). The latter also involves the state-of-the-art on the quantitative, or potentially quantitative, prediction of sandbank characteristics. On a modelling level, the most promising work results from the coupled system involving the study of hydrodynamics, sediment transport and morphology (DYER & HUNTLEY (in press)).

The main goal of the present investigation is the study of the near coastal area as a whole, although it will merely stress on the interactions and effects of the different morphological entities, like sandbanks and swales, in view of their importance for sedimentation processes. The general configuration of the study area has been discussed in Chapter 2. The current chapter will focus on the physical characterisation of the coastal system, as well morphologically as sedimentologically. On a morphological level, echosoundings form the major constituent of the dataset. Grab and boxcore sampling enabled the study of the surficial sediments and the sedimentary sequences in the area. Side-scan sonar observations have been integrated throughout this chapter. The acoustic signature is largely dependent on the morphology and the texture of the seabed, hence providing as well morphological as sedimentological information. A distinction has been made of the sandbank – swale system and the sedimentary bedforms, superimposed on the major morphological entities. On both levels, the morpho- and sediment dynamical implications are discussed. The whole of information on the characterisation of the morphology and sediments of the banks, swales and small-scale bedforms, provided more detailed information on the dynamical processes of this modern depositional environment.

Results will be presented in the form of maps that will serve as a basis for the definition and visualisation of a facies model. In this chapter, it is aimed at representing the fair-weather situation to gain insight in the every-day processes. These results will later form the basis for the determination of the temporal variation, to be discussed in the following chapter.

5.2. Sea bed topography and morphology

5.2.1. Introduction and previous work

The Southern Bight of the North Sea witnesses one of the largest morphologically complex areas of the world (15.000 km^2, McCAVE (1971)). It is characterised by elongated bedforms, that are often complex in shape. Their presence reflects the availability of sand, the asymmetry of the tides and the strength of the tidal currents. Moreover, the geometry of the bedforms is a function of flow parameters (velocity, shear stress, steadiness, flow reversal, etc.), flow depth, channelisation, fluctuating water levels and physical parameters describing the sediment (size, sorting, density, shape, etc.) (ASHLEY (1990)).

In general, large-scale flow-transverse subaqueous bedforms are found in water depths exceeding 1 m, sediment sizes coarser than 150 µm and mean current velocities greater than about 0.4 m/s. Based on experimental studies and field observations, ASHLEY (1990) concludes that flow-transverse bedforms appear to function as a resistance element to the flow and that they migrate under shear stresses imparted on the bed by the moving fluid. KENNEDY (1969) (in McCAVE (1971)) argues that small bedforms represent a perturbation of the bedload transport rate and that the larger ones are formed through a perturbation in the longitudinal direction of the suspended load transport rate.

It is generally accepted that the orientation of large-scale bedforms in relation to the tidal flow is indicative of the regional circulation pattern (STRIDE (1982)). Authors as BELDERSON et al. (1982), LANGHORNE (1982) and AMOS & KING (1984) state that, in general, their crestline is normal to the predominant direction of tidal current, though TERWINDT (1971) observed crestlines, which were not perpendicular to the main flow. From this, EISMA & KALF (1979) argued that they might also reflect fossil tidal conditions. On the basis of near-bed current meter data along the Middelkerke Bank, STOLK (1996) showed a normal direction of the small to medium dunes relative to the peak tidal currents (flood and ebb).

As with the classification of any natural system, the definition of flow-transverse bedforms is often a difficult task. In this study, the terminology and classification scheme (table 5.01) proposed in ASHLEY (1990) will be adhered to as far as possible. According to the size of the bedforms, the term *dune* is used to describe the large-scale flow-transverse subaqueous bedforms. The commonly used term *megaripple*, with a spacing between 5 and 10 m and a height of 0.2 to 1 m, corresponds with small to medium dunes. The term *sandwave*, having a spacing of more than 100 m and a height larger than 1 m, corresponds with large to very large dunes. As both form part of one large bedform class, the term dune was preferred.

Table 5.01– Classification scheme recommended by the SEPM Bedforms and bedding structures research symposium (ASHLEY (1990)).

First order descriptors:					
Size:	Spacing=	small 0.6-5 m;	medium 5-10 m;	large 10-100 m;	very large > 100 m
	Height*=	0.075-0.4 m;	0.4-0.75 m;	0.75-5 m;	> 5 m
Shape:	2-dimensional				
	3-dimensional				
Second order descriptors:					
-Superposition: simple or compound (sizes and relative orientation)					
-Sediment characteristics (size, sorting)					
Third order descriptors:					
-Bedform profile (stoss and lee slope lengths and angles)					
-Fulbeddedness (fraction of bed covered by bedforms)					
-Flow structure (time-velocity characteristics)					
-Relative strengths of opposing flows					
-Dune behaviour-migration history (vertical and horizontal accretion)					

*Height calculated using the equation $H=0.0677L^{0.8098}$ (FLEMMING (1988))

From the literature, it is generally believed that in the Southern Bight of the North Sea hardly any large bedforms can develop in water depths shallower than - 18 m as the wave effectiveness at the bed is too high (McCAVE (1971)). Small to medium dunes (megaripples) superimposed on large to very large dunes (sand waves) seem only to occur where the sand wave height exceeds 5 m (McCAVE (1971)). Moreover, based on different data sets, TERWINDT (1971) states that larger bedforms are probably absent in areas covered with coarse sand (d50 > 500 µm) and in areas where the bottom sediment contains more than 15 % of mud (d50 < 50 µm). On the Belgian continental shelf, the height of large-scale bedforms reaches a maximum of 8.6 m (LANCKNEUS & DE MOOR (1990)); on the Dutch continental shelf a maximum height of 12 m (WILKENS (1997)) can be found. Generally, the wavelength averages 200-500 m.

A number of investigators studied the morphology of the area, but only a few concentrated on its dynamics. Studies conducted by VAN VEEN (1936), HOUBOLT (1968), BASTIN (1974), GULLENTOPS et al. (1977), DE MOOR (1986a), DE MAEYER & WARTEL (1988) have a more global perspective, but apparently a thorough investigation of the spatial and temporal behaviour of morphological entities is missing. Regionally, the work of BASTIN (1974) forms a reference work and provides an ideal framework for further morphological investigations.

The morphology of the near coastal sandbank – swale system, subject of the present study, was studied by DE MAEYER & WARTEL (1988) on the basis of echosounding data. In the framework of the MASTII-STARFISH project, the near coastal area was surveyed bathymetrically and by the use of side-scan sonar imagery. Large dunes were seen in the Westdiep swale, north of the Nieuwpoort Bank and along the southern part of the Middelkerke Bank (HEYSE & VANWESENBEECK (1996)). Although linear sandbanks generally have larger dunes superimposed on them, no real evidence of their presence could be observed. Also, boxcores taken along the Stroombank and the Nieuwpoort Bank (Section 5.3) gave an indication that bedform development was strongly inhibited. Moreover, detailed bathymetric surveys with the BEASAC® along a transect perpendicular to the shoreline, comprising the eastern part of the Stroombank, the swales and the nearshore, only revealed small-scale bedforms with heights less than 0.25 m (HOUTHUYS (1996)). On the steeper landward flank of the Stroombank, only a slightly undulating surface could be measured.

5.2.2. Survey strategy

During the present study, the near coastal area has been morphologically investigated on the basis of echosoundings and side-scan sonar registrations. The observations, both in space and time, enabled to characterise the coastal system, investigate sand transport pathways and evaluate possible sediment exchanges with the more offshore areas and the coast itself.

In order to gain insight into the physical functioning of the coastal system as a whole, bathymetrical surveys were carried out, covering as well the swales as the sandbanks. Tracklines were selected in relation to the DECCA chain network, lying obliquely to the shoreline. Although the spacing of those lines was rather wide (in the order of 750 m to 1500 m), the observations provide indications of the dynamics of the area and a global sediment dynamical framework.

As mentioned before (Section 3.1), the study of sediment and morphodynamics focussed on subenvironments witnessing higher dynamics: the near coastal Baland Bank, the southern end of the Middelkerke Bank and the Ravelingen sandbank. The latter subenvironments were mainly investigated to compare bedform dynamics with those in the near coastal area. Moreover, the southern end of the Middelkerke Bank was of interest as it might witness important sediment fluxes around the bank. The Westdiep swale and the western extremity of the Stroombank were also surveyed in detail. Tracklines over the Baland Bank were spaced 50 m apart, more or less perpendicular to the strike of the bedforms; the southern part of the Middelkerke Bank was covered with lines 75 m apart. As the Ravelingen was only optionally surveyed whenever an extra high water window was available, the tracklines were sailed at a 150 m spacing. However, during three of the campaigns, time-schedule allowed a more detailed survey of this sandbank.

5.2.3. Sandbank – swale system

5.2.3.1. Characterisation of the sandbank – swale system

In this paragraph, the major morphological entities of the near coastal area like sandbanks and swales, will be described. A first morphometrical description has been given in Chapter 2; in the present paragraph, it is merely the purpose to stress specific morphological characteristics, which have important morphodynamical implications. Bedforms, systematically investigated throughout this study, will be discussed separately in the following paragraph and will only be mentioned here in general. The Ravelingen sandbank and the southern part of the Middelkerke Bank, pertaining to the Flemish Bank system, are not included in detail as reference can be made to O'SULLIVAN (1997) and DELGADO BLANCO (1998). However, the superimposed morphology of those sandbanks will be discussed in the following paragraph, as comparative evidence for the bedforms closer to the coast. The main morphological entities are:

The shoreface

Generally, the shoreface is considered "*a narrow zone seaward from the mean low water level, covered by water, over which beach sands and gravels actively oscillate with changing wave conditions*" (U.S. ARMY ENGINEERING RESEARCH CENTRE (1984) in: WIERSMA & VAN ALPHEN (1988)). In the study area, the shoreface shows a break in the slope angle around - 7 m. It consists of an upper part, frequently showing breaker bars and a flatter lower part gradually passing into the shelf area.

From the detailed bathymetrical map (HOUTHUYS & VAN SIELEGHEM (1993)), it seems that only the western part of the study area witnesses pronounced breaker banks. This broader shoreface zone corresponds to a plateau-like morphology (to a step-wise like morphology around profile 12) (Fig. 5.01). It should be noted that the - 5 m contour line, enclosing the system "Potje – Broersbank" west of Nieuwpoort (transversal distance 0 - 5 m line of 2.5 km), approaches the coast to about 500 m between Nieuwpoort and Oostende. Hence, the shoreface is narrower also. From the coastline to the Stroombank, the distance varies from approximately 4.5 km in the west to 1.7 km at the eastern extremity of the Stroombank. Echosounding profiles covering the Westdiep swale and the lower part of the shoreface (September 1997, March 1998) showed a relatively smooth seafloor, though upwards climbing small-scale features could be observed. The slope of the shoreface increases from west to east, but remains fairly low (0°10' to 1°15').

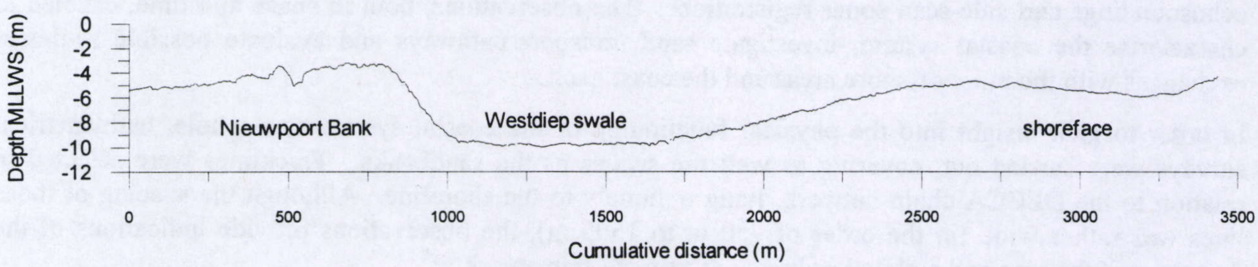


Figure 5.01 – The shoreface, west of Nieuwpoort (June 1998). Note the plateau-like morphology of the lower shoreface.

The swales

The swales are trough-like morphological entities. They separate the sandbanks or the sandbank and the shoreface. They are mostly concave in cross-section and their transition with another morphological unit is characterised by a steeping of the slope (DE MAEYER & WARTEL (1988)).

Although the swales have in general a fairly flat morphology, bathymetrical registrations along transversal profiles south of the Nieuwpoort Bank, including the Westdiep swale, the Stroombank and part of the shoreface (May 1996, September 1997, March 1998), revealed up-climbing ripples (max. height of 0.5 m, wavelength of 100 m) from the swales towards the topographic highs. Also, along the northern slope of the Westdiep swale and the southern extremity of the Noordpas, larger-scale bedforms up to 0.9 m in height could be observed (June 1998). Where the Westdiep swale interacts with the Nieuwpoort Bank, large compound dunes of 1.25 m and a wavelength of 400 m are encountered (June 1998).

Echosoundings were performed along transversal profiles covering the southern end of the Middelkerke Bank, the northern branch of the Westdiep swale, the eastern prolongation of the Nieuwpoort Bank, the Grote Rede swale (N), the Baland Bank and the Grote Rede swale (S) towards the Stroombank (December 1997, February 1998). The eastern prolongation of the Nieuwpoort Bank is particularly interesting as its height (approximately 5 m) makes it a fairly dominant morphological feature in the coastal system under consideration (Fig. 5.02). Although, a superposition of large-scale bedforms has not been observed, small-scale up-climbing bedforms are present. A distinct change in dip can be remarked along the slope separating the northern branch of the Westdiep swale from the eastern prolongation of the Nieuwpoort Bank. As will be shown later, this morphological change is attributed to differential erosion due to a difference in lithology.

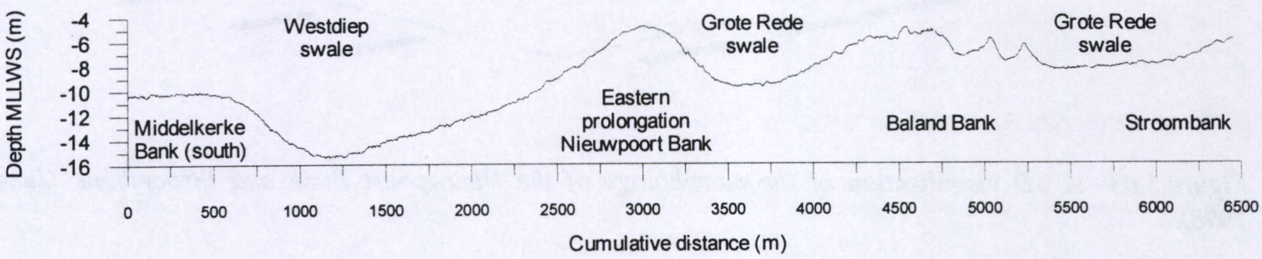


Figure 5.02 – An echosounding profile covering the southern end of the Middelkerke Bank, the northern branch of the Westdiep swale, the eastern prolongation of the Nieuwpoort Bank, the Grote Rede swale (N), the Baland Bank and the Grote Rede swale (S) towards the Stroombank (February 1998).

Nieuwpoort Bank – Stroombank

DE MAEYER & WARTEL (1988) defined a number of morphographical units on the basis of distinct changes in dip in the morphology: 1) the landward flank is characterised by a rectilinear coastward dipping slope; 2) the crest forming a narrow zone between the landward flank and the seaward flank is mostly parallel to the longitudinal axis of the bank and shows a convex cross-profile and 3) the seaward flank is characterised by a seaward dipping slope. The latter is sometimes composed of two rectilinear segments, the upper being steeper than the lower.

At some locations, echosoundings revealed up-climbing, small to medium dunes along the gentle slope of the Nieuwpoort Bank (May 1996). These were clearly observed along the western extremity of the sandbank where the dynamics may be enhanced by the vicinity of the Smal Bank and the intruding Noordpas swale.

In December 1995, tracklines along the - 7 m contour line of the Stroombank showed the presence of larger scale bedforms, however restricted to the west and central part of the bank. These bedforms were confirmed during the June 1998 campaign; they reached a height of up to 1 m. The western extremity of the Stroombank was surveyed in detail in June 1998 and revealed large-scale bedforms up to 2 m, superimposed on the morphology. The interaction area with the Baland Bank has a rather undifferentiated nature that will be discussed in Section 5.2.2.3.

Figure 5.03 demonstrates the morphology along a bathymetrical profile of the two major sandbanks, the Nieuwpoort Bank and the Stroombank. It needs emphasis that the transversal profile comprises the eastern extremity of the Nieuwpoort Bank, whilst for the Stroombank, its western part is shown. The Nieuwpoort Bank has a fairly rounded crest in opposition to the Stroombank which is sharp-crested at this location. The crests of the sandbanks are separated by a distance of about 2.2 km. Both show a pronounced asymmetry and approximate a height of 7 m from their base concavities. The echosounding profiles sailed as well in a longitudinal as transversal sense (June 1998) proved that only a restricted area of the sandbank was covered by larger-scale bedforms. Moreover, the steep landward flank of the bank clearly indicated upward climbing bedforms. The crest of the bank was shaped in a seaward direction. It should be noted that the profile was sailed in June 1998, under fair-weather conditions during neap tide in a time span of one hour before to up to one hour after high water.

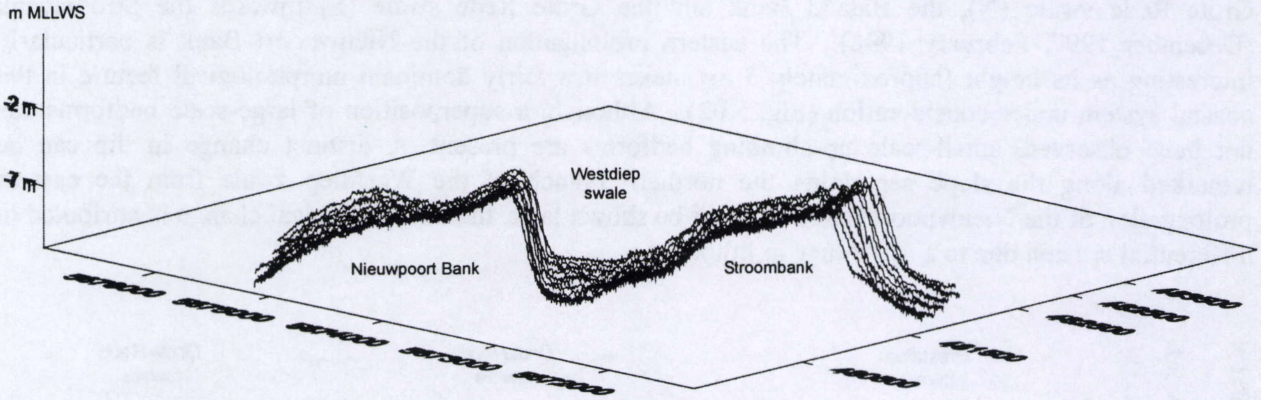


Figure 5.03 – A 3D visualisation of the morphology of the Nieuwpoort Bank and Stroombank (June 1998).

Baland Bank

The morphology of the Baland Bank area can best be visualised by a spatial diagram of echosounding profiles. Figure 5.04A is a representation of the profiles, sailed in March 1998. Interpolation of the data led to a digital elevation model of the area (Fig. 5.04B). From the spatial diagram, it is clear that the area merely represents an anomaly in the sandbank – swale system. The morphological features are well confined, but fade out in the surrounding environment. The profiles also demonstrate the difficulty to delineate the bank itself. A zone, contoured by the - 7 m line, seems to represent the main body of the bank. The width varies between approximately 1 km in the south to 250 m along the central lying profiles. From this, one could even speculate that the bank merely resembles a sharp-crested very large dune with a maximum height of 4 m. The slope of the latter varies from less than 0°5' at the base to a maximum of 5°5' near the crest. Towards the south, a berm-like morphology of around 3 m in height is superimposed by very large dunes, which can attain heights of 3 m. The northern part of the area represents an undulating surface. The area where the Baland Bank interacts with the Nieuwpoort Bank has a slightly rougher morphology. From multibeam echosoundings carried out by the *Belgian Waterways Coast Division*, it seems appropriate to morphologically delineate the bank by its - 7 m contour line. The shallowest depths measured were - 3.2 m (51°13.75', 002°46.25' or UTM 483998, 5675451) in a position aligned with the axis of the Westdiep swale. Along the southern part of the bank, a minimum depth of - 3.8 m is measured (51°13.18', 002°45.93' or UTM 483622, 5674396)*. Side-scan sonar observations also confirm the above mentioned delineation of the bank (Appendix B).

Ravelingen

Comparable to the Baland Bank, the Ravelingen is also contoured by the - 7 m line. From multibeam echosoundings carried out by the *Belgian Waterways Coast Division* (November 1997), a minimum depth of - 4.1 m could be distinguished in the southern part of the bank (51°16.53', 002°50.68' or UTM 489164, 5680590)*. Reference here is made to DELGADO BLANCO (1998). A spatial diagram of the echosounding profiles sailed in March 1998 are presented in Figure 5.05.

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*Depths were corrected for on the nautical charts (BAZ ("*Berichten aan Zeevarenden*") 29/01/98), published by the *Belgian Waterways Coast Division* at Oostende.

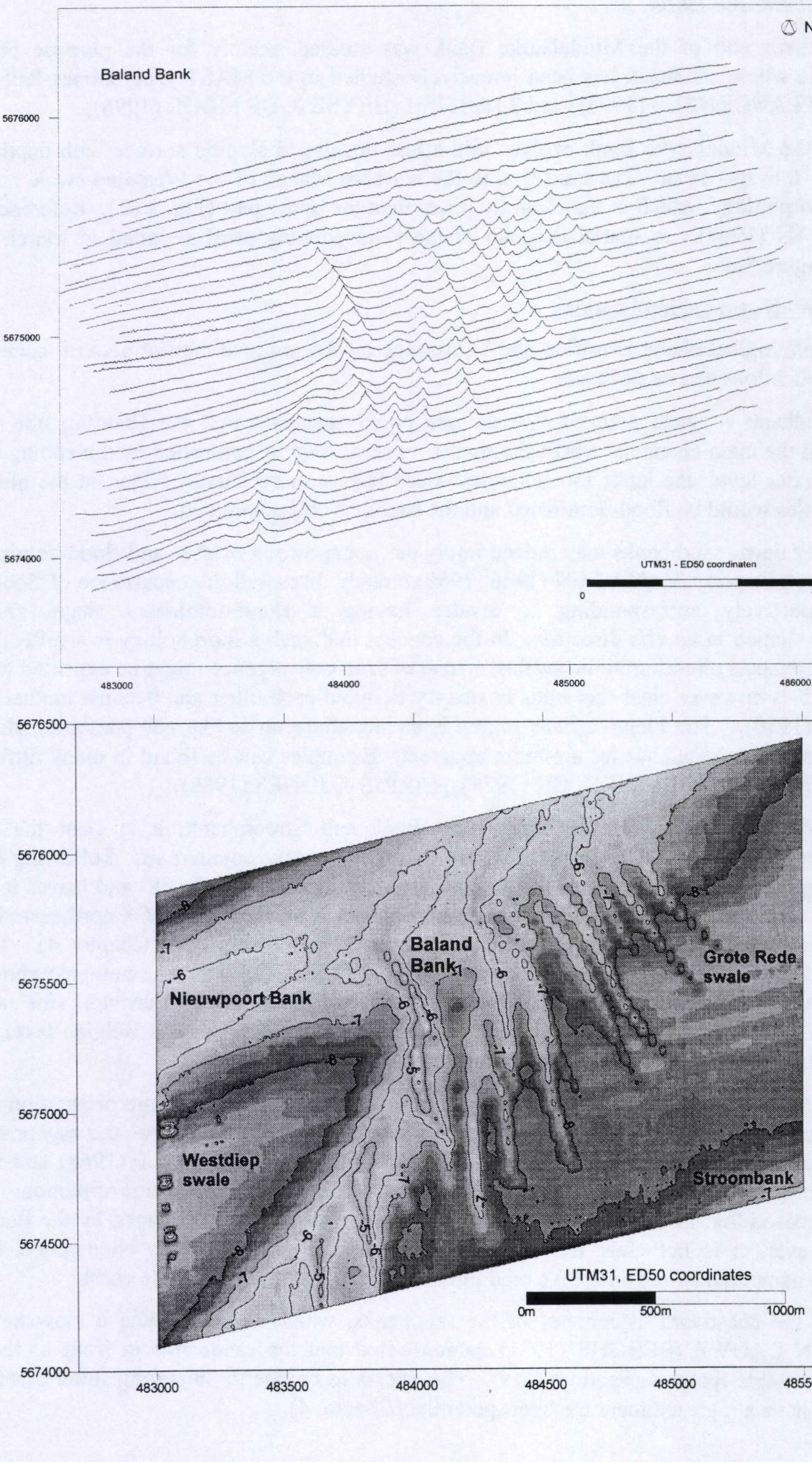


Figure 5.04 – Baland Bank. A. Spatial diagram of the echosounding profiles (March 1998); B. A digital elevation model of the Baland Bank area. Depths are indicated in m below MLLWS; survey lines were spaced every 50 m (March 1998).

Southern Middelkerke Bank

Only the southern end of the Middelkerke Bank was studied, mainly for the purpose of bedform dynamics. The whole sandbank has been intensively studied in the MAST programmes RESECUSED (DE MOOR & LANCKNEUS (1993)) and STARFISH (HEYSE & DE MOOR (1996)).

To the south, the Middelkerke Bank evolves into a less developed sloping surface with depths ranging from roughly - 8 m to - 14 m. The transition to the northern branch of the Westdiep swale resembles a plateau-like morphology, which is significantly lower than the upper part (Fig. 5.02). Reference is made to O'SULLIVAN (1997). A spatial diagram of the echosounding profiles sailed in March 1998 are presented in Figure 5.06.

5.2.3.2. Morpho-dynamical implications

From the morphological characterisation and knowledge on the regional current pattern, some morpho-dynamical implications can be deduced.

Given the sandbank – swale coupled system, one could speculate that the flooding tide is mainly concentrated in the main channels, whilst the shallower areas may be controlled by the ebbing tide. Due to the lower water level, the latter forces could indeed have a more intense effect on the morphology. Hence, the swales would be flood-dominated and the shallows ebb-dominated.

The presence of linear sand banks may indeed imply the juxtaposition of ebb- and flood-dominant zones of net sediment transport. VAN VEEN (1936; 1950) already discussed the occurrence of flood and ebb parabola, respectively corresponding to swales having a flood-dominated shape and swales predominantly shaped in an ebb direction. In the concept that such a morphology is a reflection of the residual sand transport direction in the swales, a zone of sand convergence might be expected where both swales meet. It is however clear that both swales try to avoid each other and become mutually evasive (VAN VEEN (1950)). The Flemish Bank region is mainly characterised by ebb parabola, whilst closer to the coast flood-dominated swales are more apparent. Examples can be found in many different tidal systems (ROBINSON (1966), LUDWICK (1974), HARRIS & JONES (1988)).

Investigating the morphology of the Nieuwpoort Bank and Stroombank, it is clear that both are characterised by a broader western extremity and a narrow eastern counterpart. Following CASTON (1981), it is supposed that sand enters the bank system along the broader "head" and leaves it along the narrow "tail'. This means that the morphology of the banks is an indication of a northeastern residual transport, which can be supported by the flood-dominant regional transport (Chapter 4). Through a combination of the Coriolis effect and bottom drag (HUTHNANCE (1973)), the sandbanks show an anti-clockwise deflected orientation with respect to the rectilinear tidal currents (for a review, PATTIARATCHI & COLLINS (1987), DYER & HUNTLEY (in press); on a Belgian level, the tide-topography effect has been hydrodynamically investigated by YANG (1998)).

As observed for several Belgian sandbanks (i.e. GAO et al. (1994)), this oblique orientation induces a transversal component of sediment transport towards the crestline. In that sense, the asymmetry of the sandbanks also confirms the overruling flood current. Authors as HOUBOLT (1968) and CASTON (1972) also postulated that the asymmetry of sandbanks reflects their migration direction. BASTIN (1974) hypothesised that the sandbanks could be seen as remnants of banks shaped by the flood (flood-banks). However, it is not clear to what extend the lateral growth of the Nieuwpoort Bank and Stroombank is hampered by the extensive mud plume along the central part of the coast.

Regardless of the coastward asymmetry of the sandbanks, which would assume a movement in that direction, VAN CAUWENBERGHE (1971) demonstrated that the sandbanks in front of the Belgian coast are fairly stable features (Section 2.2.4). This seems to be due to the strong flood currents in the swales, which have a high sediment transport potential (Chapter 4).

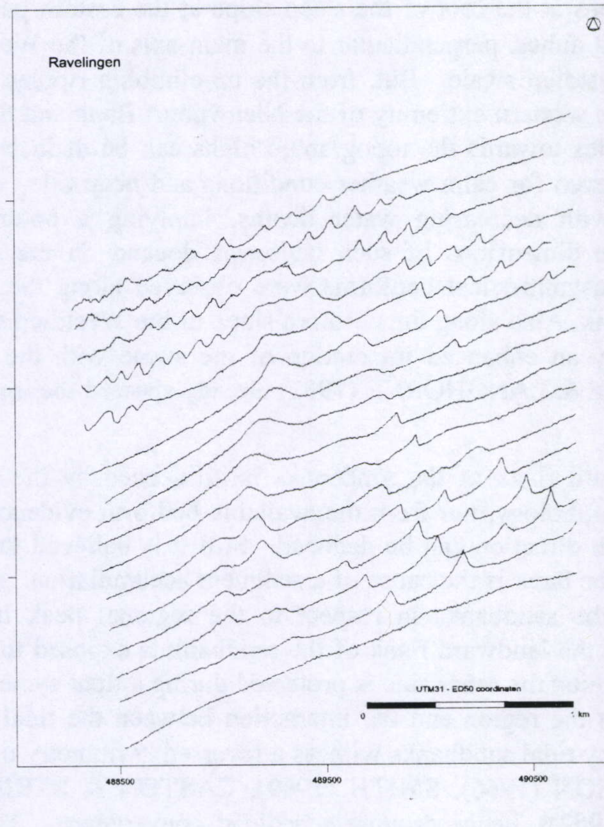


Figure 5.05 – Ravelingen. Spatial diagram of the echosounding profiles (March 1998).

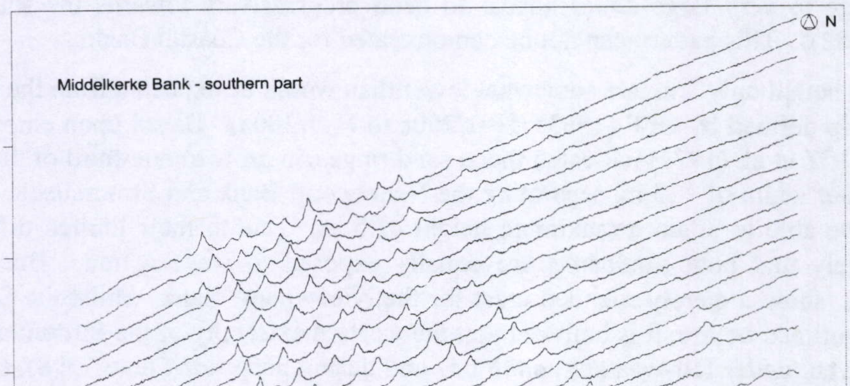


Figure 5.06 – Southern part of the Middelkerke Bank. Spatial diagram of the echosounding profiles (March 1998).

Side-scan sonar observations at the foot of the steep slope at the eastern part of the Nieuwpoort Bank, showed straight-crested 2D dunes, perpendicular to the main axis of the Westdiep swale and a possible scoured surface in the Westdiep swale. But, from the up-climbing ripples observed somewhat higher along the steep slope at the western extremity of the Nieuwpoort Bank and Stroombank, also a transport of sediment from the swales towards the topographic highs can be deduced. This holds true under a variety of circumstances, even for calm weather conditions and neap tide. From this, it seems evident that currents accelerate with decreasing water depths, implying a potential for upslope sediment movement. However, the dimensions of such bedforms depend on the local dynamics. As such, pronounced up-climbing, asymmetrical bedforms were observed along the steep slope at the western extremity of the Stroombank. Also along the northern slope of the Westdiep swale, larger bedforms were found, probably caused by an enhanced interaction of the swale with the Nieuwpoort Bank and the Noordpas swale. McCAVE & LANGHORNE (1982) already showed the importance of the dynamics at the tails of sandbanks.

To what extend the seaward flank of the sandbanks is influenced by the ebb tidal currents, remains unclear. Nor from the morphology, nor from the available bedform evidence, a significant transport of sediment in a southwestern direction can be deduced. Still it is believed that an asymmetry in current strength on either side of the bank is the cause of a sediment accumulation. Analoguous to KENYON et al. (1981), the angle of the sandbanks in respect to the regional peak tidal current and the swale configuration, implies that the landward flank of the sandbank is exposed to a greater amount of tidally induced bottom friction, whilst the other side is protected during a tidal cycle. The whole is the result of the tidal conditions within the region and the interaction between the tidal components (PINGREE & GRIFFITHS (1979)). Many tidal sandbanks witness a reversed asymmetry of bedforms along both sides of the bank (i.e. ROBINSON (1966), SMITH (1969), CASTON & STRIDE (1970), HUTHNANCE (1973), LANGHORNE (1982)), hence proving a bedload convergence. The crestlines of linear sand banks are thought to be formed by a convergence of transport patterns (CASTON (1972)), so in plan view, the large to very large dunes appear to bend progressively towards the shallow bank crestline (STRIDE (1982)). This pattern can not be demonstrated for the Coastal Banks.

The banks, in height only 7 m, are somewhat lower than would be expected from the height (H) – spacing (a) relationship defined by OFF (1963) (H=1/200a to H=1/300a). Based upon empirical measurements, BOKUNIEWICZ et al. (1977) indicated that a sand ridge can grow to one-third of the water depth. For a maximum water depth of - 15 m, separating the Nieuwpoort Bank and Stroombank, this means that they should only be able to attain a maximum height of 5 m. Due to their limited difference in height, it would be likely that both sandbanks are equally exposed to wave action. But transversal profiles covering both, show a merely rounded crest for the Nieuwpoort Bank, whilst the Stroombank is sharp-crested. As outlined before, it is believed that the western extremity of the Stroombank witnesses higher dynamics. Even, under fair-weather conditions and during neap tide (June 1998), the crest seems to be shaped by upwards accelerating currents, from the swales towards the top. This means that the crest of the Stroombank may become a bottom current convergence zone at times of maximum sand transport. However, it seems likely that the top is deteriorated under heavier weather conditions. It is not clear in what way such currents are responsible for the northern shift of the western part of the Stroombank. Generally, it can be concluded that the height of sandbanks is determined by the balance between the rate of diffusion of material due to the wind-wave internal velocity field and the growth rate due to the basic flow (SMITH (1969)). Moreover, it seems likely that the dimensions of the banks are also constraint by the adjacent shoreline.

In Chapter 2, it was already outlined that the curvilinear Baland Bank can be seen as the shallow, eastern extremity of the Westdiep swale. The main body of this small sandbank has an almost N-S orientation, implying that the angle between the local peak tidal current flow and the sandbank crest is more or less normal. In a more regional framework, the Baland Bank is located in the interaction area of two mutually evasive tidal channels; hence theoretically leading to a bedload convergence. In that perspective, the Baland Bank can be seen as an accumulation of sand. However, a difference in the transport rate of the sediment must exist in order to transport more sand into the system than is being transported out of it. Indeed, it is believed that in the interaction zone Westdiep swale – Baland Bank, the tidal currents are inherently unsteady and that localised processes or instabilities help in the build-up and maintenance of the sandbank. Acceleration of the current is supposed as the tide funnels through the narrowest part of the Westdiep swale, whilst a deceleration is expected in the Baland Bank area (the divergent point). Although the flood dominates the ebb, the latter is strong enough to, at least, contribute to the bedload convergence. Due to the difference in water level, it seems likely that the ebb tidal current controls bedload transport in the shallow areas. The counter action of flood and ebb currents is demonstrated by the S-shape morphology of the sandbank. A hypothesis on the origin of the Baland Bank in a broader geological framework will be discussed in the following chapter.

Noteworthy is the presence of the eastern prolongation of the Nieuwpoort Bank (Fig. 5.02). Given its height, it seems evident that this "bank" shelters the sandbank – swale morphology south of it. Moreover, it may protect the Baland Bank from northwestern influences.

The morphology of the Ravelingen area resembles to a certain extend the morphology of the Baland Bank. In this case, it is the northern branch of the Westdiep swale, which is shaping the bank centrally. The southern part seems also to be shaped by residual ebbing forces.

From the plateau-like morphology of the Middelkerke Bank, it can be suspected that the low-lying part is more under the influence of processes similar to those controlling the near coastal area.

5.2.4. Sedimentary bedforms

5.2.4.1. Characterisation and distribution of the bedforms in the study area

Field observations with the aim of detecting bedforms started in December 1995, the latest being in September 1998, with a frequency of 4 to 5 campaigns a year. From the reconnaissance survey in December 1995 using side-scan sonar imagery, most of the area seemed to be devoid of bedforms. Only the acoustical registrations showed larger dunes along the western part and tail of the Stroombank, in the interaction zone of the Nieuwpoort Bank and Stroombank, along the Baland Bank and along the southern end of the Middelkerke Bank. Together with the results of the extensive boxcoring campaign in July 1994 (STOLK (1996), Section 5.3), this led to the conclusion that only the area, shallower than roughly - 8 m MLLWS was of interest for the study of morpho- and sediment dynamics. Subsequently, this zone was surveyed in detail.

The classification scheme of ASHLEY (1990) will be used in the description of the bedforms. However, the sediment characteristics of the dunes will be discussed in Section 5.3.3.3. The dune behaviour-migration history will be dealt with in the following chapter.

Baland Bank area

As mentioned in Section 5.2.3.1, the morphology of the Baland Bank area is most peculiar. In December 1995, echosoundings and side-scan sonar registrations witnessed the presence of large dunes of up to 2 m 30. In February 1996, the whole area was investigated in detail and revealed a field of dunes, east of the Baland Bank. Side-scan sonar images gave evidence of quasi straight-crested bedforms, having a spacing of more than 100 m; this justified the usage of the term "two-dimensional very large dunes". Side-scan sonar mosaicing (lines spaced 50 m apart) was carried out in September 1996. A fully corrected map can be found in Appendix B. The following description is based on these results, though the observations were confirmed during subsequent campaigns. From the bathymetrical registrations, bedform heights of up to 2 - 3 m could be deduced. The strike of the 2D dunes gradually varied from 140° in the northeastern part, up to 183° in the vicinity of the bank itself. Wavelength values ranged between 125 and 200 m. Given the restricted area in which the dunes occur, each dune has a fairly lateral continuity. Branching of the crestlines may occur. Although the recordings only vaguely showed a superposition of small to medium dunes, the term "compound dunes" seemed to be valid, as was expected from the echosounding profiles. In September 1996, the asymmetry of the very large dunes pointed in a southwestern direction (Fig 6.15, Section 6.4.2). This seemed to be exceptional as this phenomenon was not observed during the other 12 campaigns, also sailed in a timespan of 3 hr before up to 4 hr after high water. Also, the side-scan sonar registrations showed individual fields of small to medium dunes, having a spacing of maximum 5 m. Mostly, they witnessed straight, 2D crestline patterns, with a strike around 135°. They were observed in the troughs of the larger dunes, in water depths deeper than - 7 m, but seem to be absent in the shallower regions. Hence, the fulbeddedness of the bedforms is difficult to discuss. At the time of recording, the asymmetry pointed in a northeastern direction.

The side-scan sonar observations over the shallowest regions revealed a ripple-like morphology, superimposed on the crestline of the small sandbank and dipping in a coastward direction. Apart from this small-scale morphology, the crestline of the bank, resembled merely a very large dune, having a height of 3 to 4 m.

Most interesting is the western, steeper slope of the Baland Bank. Along the slope, from roughly - 8 m to - 6 m, well-defined small to medium sized dunes could be observed. Their spacing varied around 4-5 m, the strike around 120°. A slight veering to 130° occurred in a northwards direction. The steep side of those bedforms pointed in a northeastern direction. In the Westdiep swale, deeper than - 8 m, the presence of molluscs is suspected from the side-scan sonar observations (Appendix B).

The merely undulating northern part of the Baland Bank area also witnessed the presence of small to medium dunes, though no large dunes could be observed. They have the same dimensions and asymmetry as their southern counterparts, though their strike varied around 100°.

From the detailed surveys along the Baland Bank, it was suspected a transport pathway might exist from the Stroombank to the Baland Bank. Indeed, the lowermost profiles show large dunes superimposed on a berm-like morphology. Tracklines sailed south of these profiles (March 1998), confirmed a rougher morphology along the eastern slope of the Westdiep swale, but showed only minor perturbations along the berm. The height of this morphological entity decreases gradually towards the south.

Nieuwpoort Bank - Stroombank

The presence of bedforms along the Nieuwpoort Bank and Stroombank has already been outlined in Section 5.2.3.1; they were not systematically investigated, nor was their geometry studied in detail.

The bedforms in the interaction zone of the Nieuwpoort Bank and Stroombank (narrowest part of the Westdiep swale) were surveyed in May, September and November of 1996, and March 1998. Although merely dunes with a less-differentiated morphology characterised this area, there was one pronounced very large dune of almost 2 m in height (Fig. 5.07). Generally, the height of the bedforms ranged between 0.50 and 1.25 m, with a wavelength varying from 100 to 150 m. A slight veering of the strike of the dunes could be observed from 200° for the most western dunes up to 136° for the easternmost dune. The asymmetries of all dune-like structures always pointed in a northeastern direction. Remarkable is the restricted area over which bedforms occur. They could only be observed over a distance of 1600 m from the western end of the Stroombank in water depths shallower than - 9 m; this corresponds with the narrowest part of the Westdiep swale. Side-scan sonar images failed to show the crestlines of these dunes, though patches with molluscs appeared downstream of the steep side of these bedforms. Shading effects bared also witness of their presence. It was to note that in September 1996, the shape of the - 10 m contour line, delineated zones of a lighter reflectivity. It is believed that these correspond to sandy patches or they may also indicate a wiping out event (Fig. 5.08). Deeper than - 10 m, no significant bedforms were observed. Along the steeper northern flank of the Westdiep swale, where interaction occurs with the Nieuwpoort Bank, a sharp delineation of the sandbank – swale system can be observed (Fig. 5.09). Side-scan sonar observations showed at one channel very clean medium dunes, whilst the other channel displayed a complete other structure, even showing trawl marks. From the side-scan sonar images, one could even suggest the occurrence of an erosive surface.

A survey covering the western part of the Stroombank, showed that the above mentioned, largest dune in the swale was not an extension of a dune system on the bank, but was restricted to the slope of the swale (Fig. 5.07).

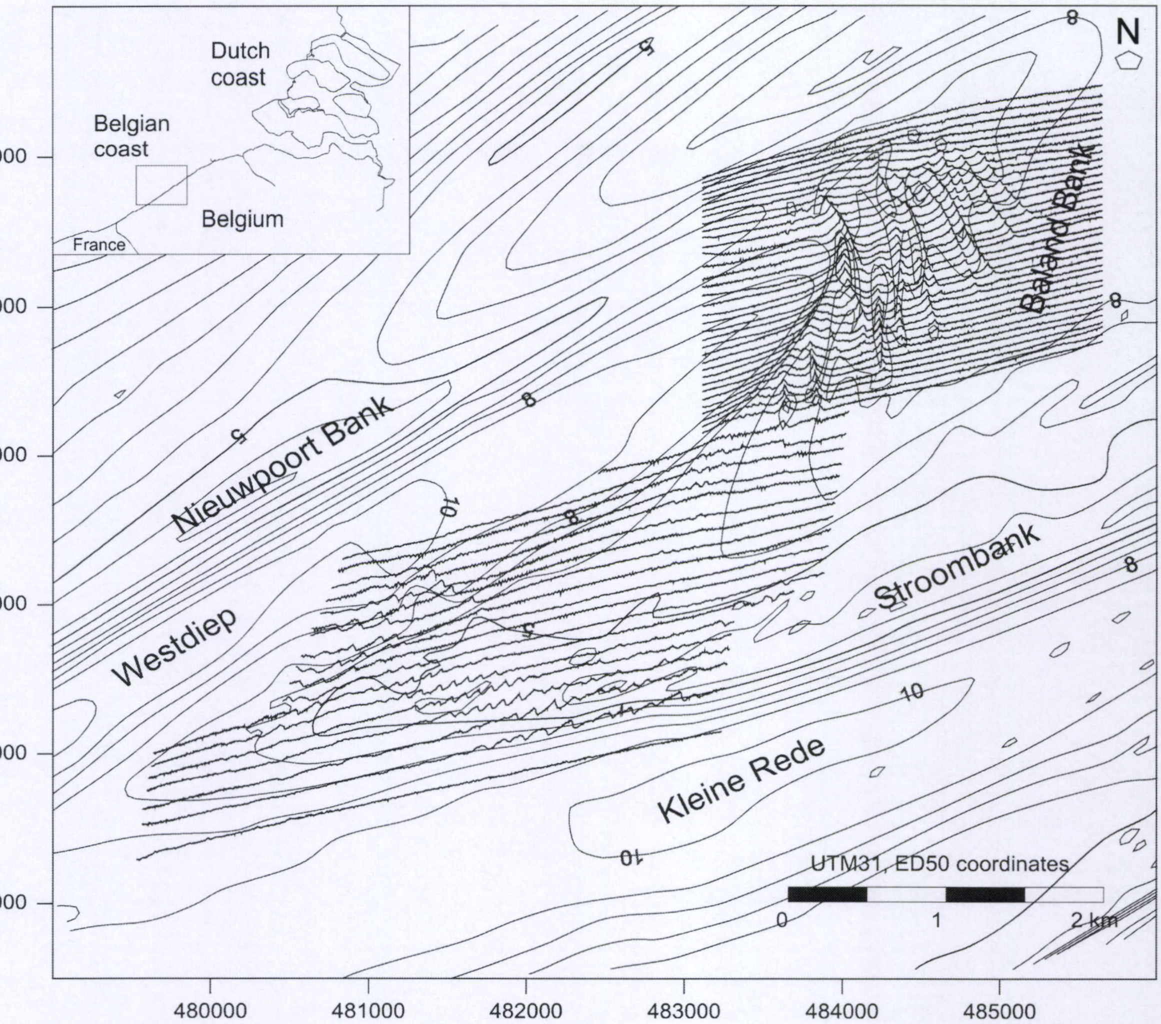


Figure 5.07 – A compilation of echosounding profiles covering the Westdiep swale, the western extremity of the Stroombank, the interaction zone of the Stroombank and the Baland Bank and the Baland Bank (data of March 1998, June 1998). The profiles are superimposed on the bathymetric workchart of HOUTHUYS AND VAN SIELEGHEM (1993).

On the Stroombank, the height of the very large dunes reached a maximum of up to 2 m, having a wavelength of 150 - 200 m. Sometimes, they were superimposed with smaller scale ripple-like features. Although their presence is fairly irregular, bedforms are expected from a depth of - 7 m. At the western end of the Stroombank, a succession of large dunes of about 1 m in height and a wavelength of 100 m could be observed, in water depths shallower than - 5 m. These bedforms quickly die out towards the central part of the bank.

Ravelingen

Dune heights in the Ravelingen area amount up to 3.4 m (March 1998). The most common wavelengths ranged between 100 and 200 m. The strike of the bedforms is NW – SE oriented, varying around 140°. The steep side of the majority of the bedforms pointed in a northeastern direction, though in the northwestern part some symmetrical dunes were found. Reference is made to DELGADO BLANCO (1998). From side-scan sonar registrations carried out in February 1996, no small to medium dunes could be deduced. This may be due to the poor quality of the data, although on the adjacent Oostende Bank fulbedded, very large dunes could be observed.

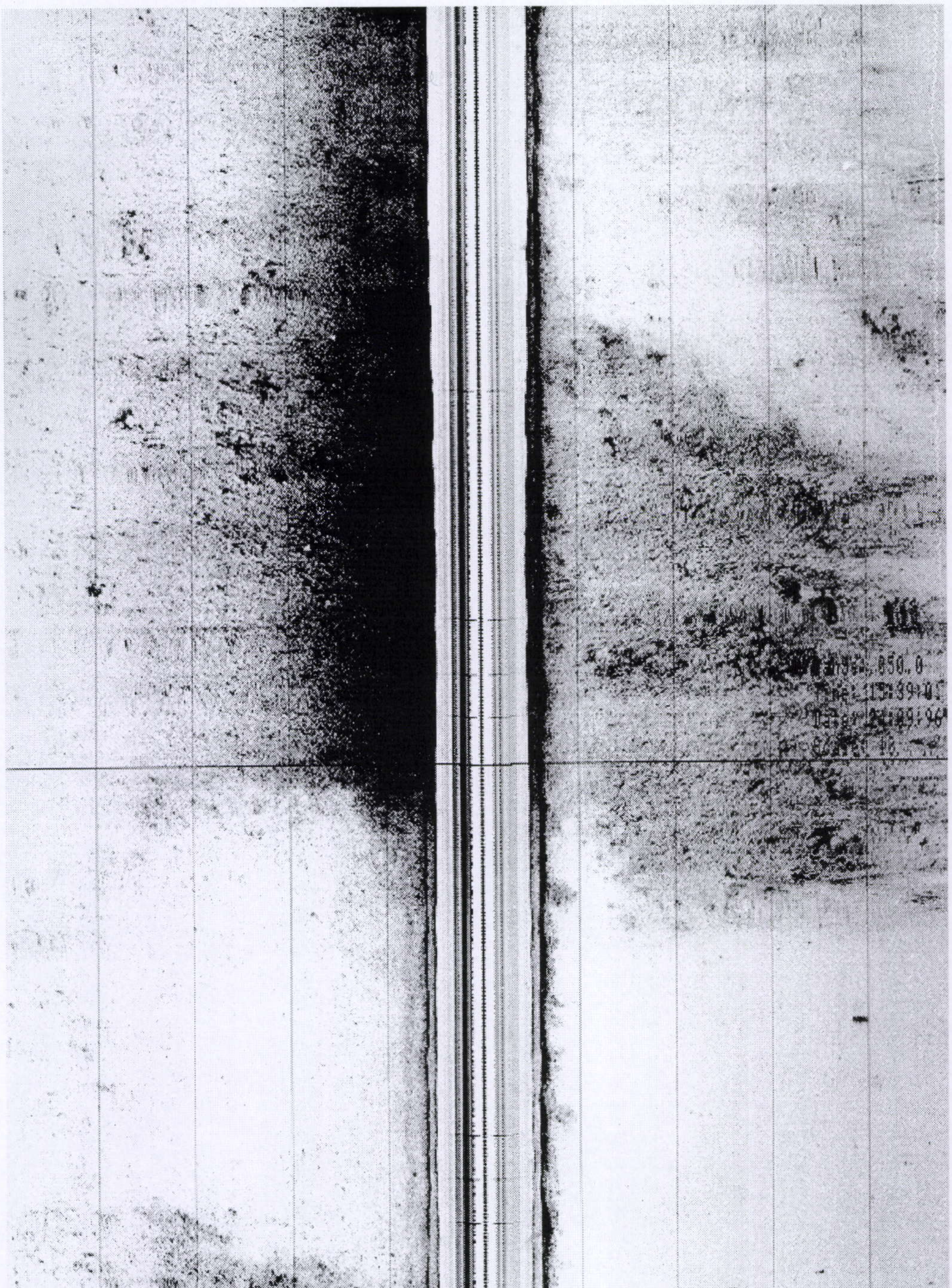


Figure 5.08 – Side-scan sonar observations in the Westdiep swale (September 1996). Integration with bathymetrical data learns that the zones of lighter reflectivity align with the - 10 m contourline.

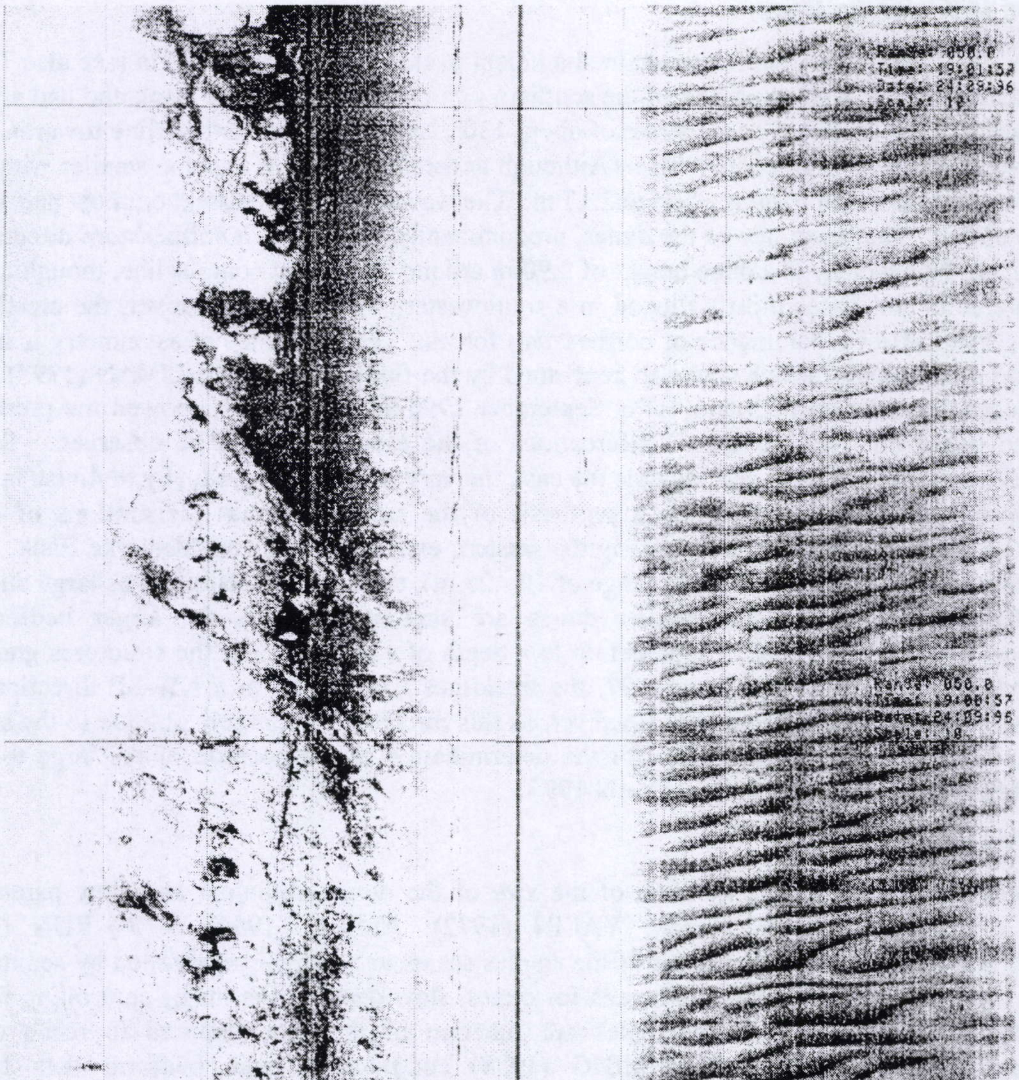


Figure 5.09 – Side-scan sonar observations in the interaction zone of the Westdiep swale and the Nieuwpoort Bank witnessing the sharp delineation between the sandbank – swale system (September 1996).

Southern Middelkerke Bank

In March 1998, the highest bedforms attained a height in the range of 2.75-3.00 m (see also Table 5.02). These occurred in the shallowest part of the southern part of the Middelkerke Bank and had a wavelength varying around 150 to 200 m and a strike of about 130°. A bending of the crestline towards 145° could be observed near the - 10 m contour line. Although generally the dunes become smaller with increasing depth, they can still reach heights of up to 2.17 m. The wavelength in this southernmost part varied from 180 m to 650 m. The steep side of the dunes, predominantly, pointed in a northeastern direction or were symmetrical. Noteworthy is a dune height of 2.90 m around the - 10 m contour line, though to the north, the steep side of the dunes mostly dipped in a southwestern direction. Moreover, the crestlines of the northern dunes reflect a dominance of northeastern forces. The difference of asymmetry is independent of the time of surveying, which was also confirmed by the findings of O'SULLIVAN (1997). Side-scan sonar images, recorded in February 1996, September 1996 and May 1997, showed the presence of 2D compound dunes all over the area. Bifurcations of the crestlines could be observed. Towards the western extremity of the bank and towards the east, the very large dunes gradually diminish in height and finally disappear. Figure 5.10 gives a synthesis of the side-scan sonar registrations of May 1997. Remark the presence of the bedforms along the western extremity of the Middelkerke Bank. According to their dimensions (wavelength in the range of 10 - 25 m), these can be classified as large dunes. South of the Middelkerke Bank, the smaller dunes are superimposed on the larger bedforms. The fulbeddeddness of the seafloor is apparent up to a depth of - 12 m; deeper the structures gradually fade out. It has to be noted that in May 1997, the tracklines were sailed in a NW-SE direction to ensure optimal side-scan sonar registrations. However, as this direction was largely oblique to the strike of the crestline, these data were not suitable for the determination of the position of the large to very large dunes. Reference is made to O'SULLIVAN 1997.

5.2.4.2. Dimensional analysis

Several equations exist for the relation of the size of the dunes, sediment and flow parameters (e.g. ALLEN (1968); KENNEDY (1969); YALIN (1972); ALLEN (1984); VAN RIJN (1984) and FLEMMING (1988)). The dimensions of the ripples seems to be largely controlled by sediment texture (size, sorting, shape, composition), whereas for dunes, flow depth is the major controlling factor. The dimensions of small-scale current ripples are function of the time required to reach equilibrium morphology (BAAS (1994)). FLEMMING (1988) compiled a large bedform data base (1491 observations) and derived to best fit functions, relating bedform height and wavelength, which are applicable to both ripples and dunes. However, AMOS & KING (1984), point out the second order effects that may alter the relationship height to wavelength: grain diameter, current speed, wave destruction and water depth. Current reversal does not affect the relationship. It should be noted that the formulae were derived for steady, unidirectional flows.

A comparison of the four environments demonstrates that the sandbank areas have their highest dunes around 3 m. Although the Ravelingen witnesses a maximum value of 3.4 m, the majority of the large dunes only reaches heights less than 1 m, whilst in the Baland Bank area, dunes in the range of 1.25 to 1.50 m are most common. The field data of March 1998 was chosen, as it was the only campaign during which the four environments were surveyed contemporaneously. Moreover, the meteorological conditions during the survey led to a very good quality of the data.

The percentage of dunes with an asymmetry in a northeastern direction is highest in the Westdiep swale, but also overrules in the other areas. The relative high occurrence of symmetrical dunes is characteristic for the sandbank areas. Although the results represent fair-weather conditions, it should be noted that the dune heights in the Westdiep swale in March 1998 are lower than those surveyed in May, September and November of 1996. Figure 5.11 represents histograms of the dune heights and the angle of the steep slopes of the dunes for these four environments. Except for the Ravelingen, the most common angle for the steepest slope of the dunes varies in the range 1 – 2°. This is low, compared to the general values found on the Middelkerke Bank. LANCKNEUS & DE MOOR (1994) reported 2 – 3° as most common range, though values up to 10° were also found. Values of up to 10° are very common (McCave (1985)).

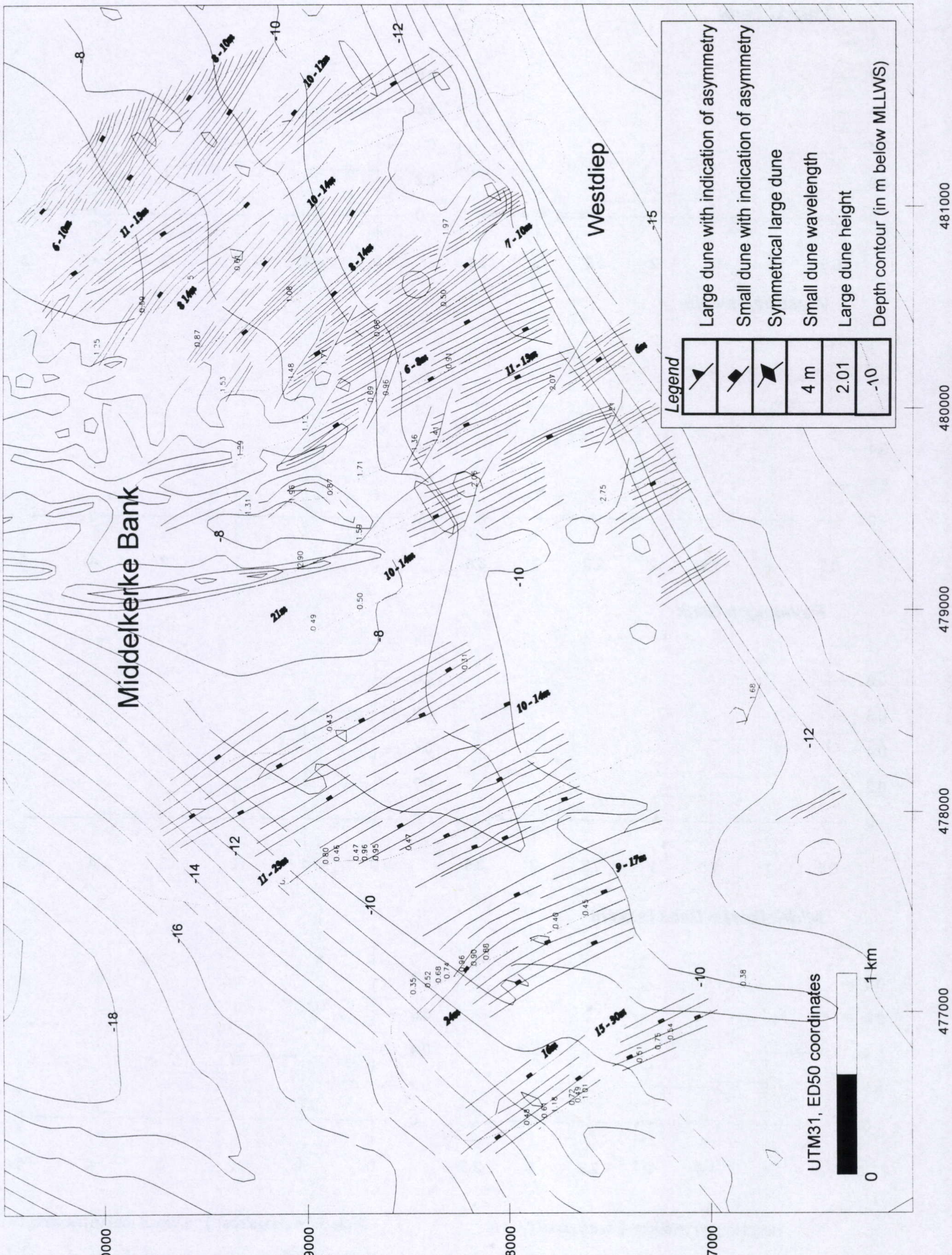


Figure 5.10 – Southern part of the Middelkerke Bank. Synthesis of side-scan sonar registrations (May 1997) (O'SULLIVAN 1997).

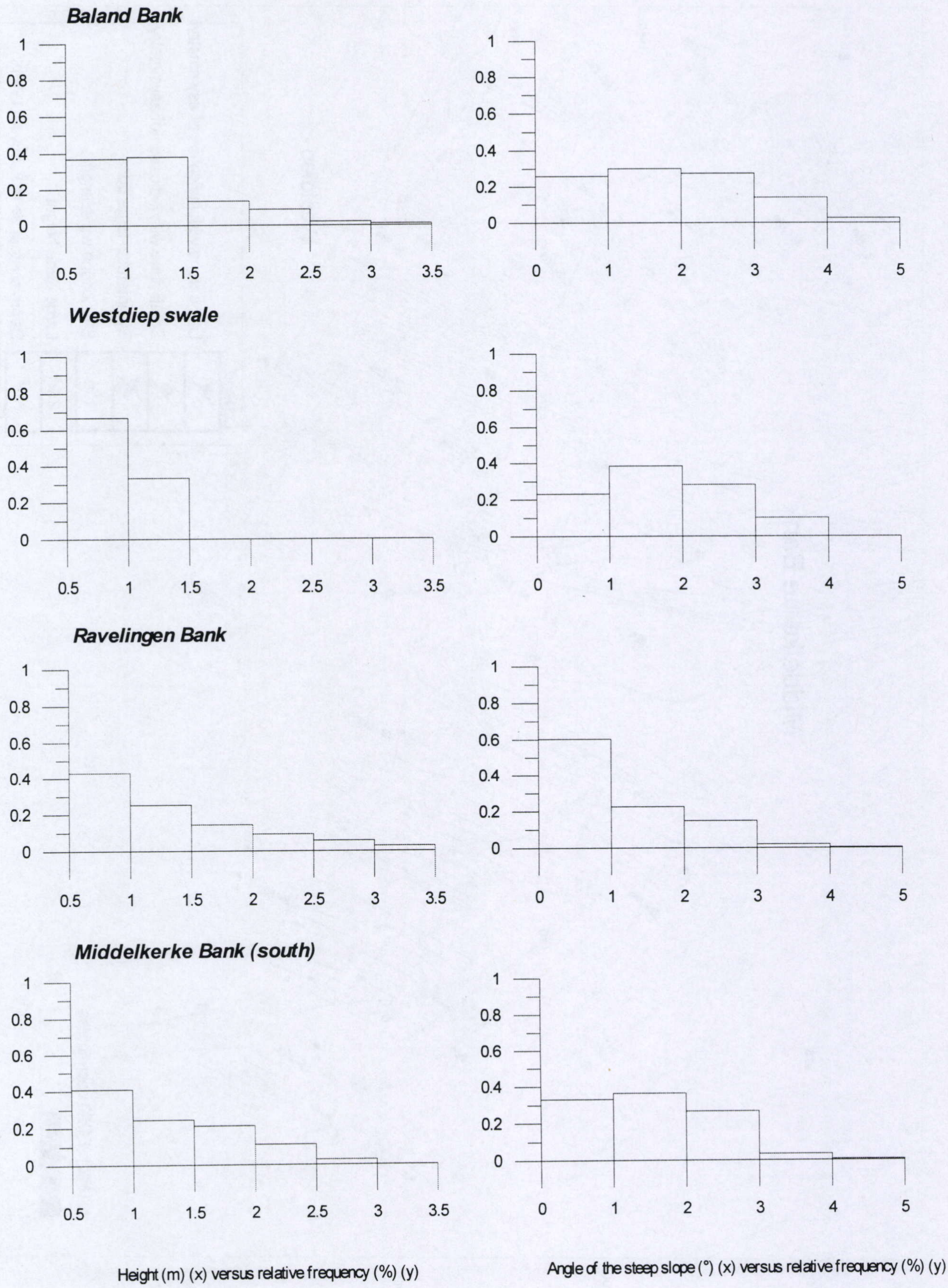


Figure 5.11 – Histograms showing the distribution of the height of the bedforms and the angles of their slope in the four subenvironments (March 1998).

However, it should be noted that in the latter only the highest observation per dune was taken into account, whereas in the present study, all data points are used for the geometrical calculations.

Table 5.02– Frequency of occurrence (in %) of bedform characteristics along the areas Baland Bank, Westdiep swale, the southern end of the Middelkerke Bank and the Ravelingen Bank (March 1998).

	Height	***Baland Bank***	***Westdiep swale***	***Ravelingen Bank***	***Middelkerke Bank (south)***
small dunes	0.50-0.75 m	10.7	25	13.4	15.5
large dunes	0.75-1.00 m	19.1	31.3	**19.8**	**18**
	1.00-1.25 m	**20.8**	**37.5**	16.1	13
	1.25-1.50 m	**21.3**	6.3	12.4	13
	1.50-1.75 m	11.2	0	13.4	15.5
	1.75-2.00 m	3.9	0	4.1	9.3
	2.00-2.25 m	6.7	0	3.7	9.3
	2.25-2.50 m	2.2	0	6.9	3.1
	2.50-2.75 m	1.7	0	4.1	1.2
	2.75-3.00 m	1.1	0	2.8	1.9
very large dunes	3.00-3.25 m	1.1	0	1.8	0
	3.25-3.50 m	0	0	1.4	0
	3.50-3.75 m	0	0	0	0
	3.75-4.00 m	0	0	0	0
Max. height		3.2 m	1.3 m	3.4 m	2.91 m
% Flood		**66**	**95**	**69**	**41**
% Ebb		10	0	12	25
% Symmetrical		24	5	19	34

Figure 5.12 shows some relations plotted for the large dunes (> 0.75 m) in the Baland Bank dune area. In order to support the findings, the results of 5 campaigns were used. The height versus wavelength relation shows smaller height values than would be calculated from the wavelength, using the equations of FLEMMING (1988) or ALLEN (1984). A cloud can be observed, showing that a range of dune heights can be found for a range of wavelengths and that no real relation between both can be determined. This discrepancy will be discussed in the following paragraph. For the figure 'asymmetry index versus water depth', a distinction was made between progressive and symmetrical dunes, independent of the direction in which the dunes were dipping. This was done as it was expected that depending on depth, the dunes would show a degree in vulnerability with regard for the hydrodynamic forces. However, no relation is seen and apparently, as well progressive and symmetrical dunes can be found in the range of water depths. The plot showing the height of the dunes versus the water depth is most interesting. Contrasting to the relationship of ALLEN (1984), it seems that the highest dunes occur in the shallowest areas. In this figure, also the bedforms with heights less than 0.75 m are included. This is also discussed in the following paragraph. The wavelength versus the water depth shows no coherent pattern, and apparently the variety of wavelengths occurs in the range of water depths, from roughly -3 to -8 m.

The same trend, but with more scatter is found, if the dune characteristics of the four subenvironments, i.e. Baland Bank, Westdiep swale, Middelkerke Bank (south) and the Ravelingen, are plotted together (Fig. 5.13). The height of the dunes remains smaller than the calculated values. In all environments, symmetrical dunes occur regularly. The height compared to the water depth confirms the presence of higher dunes in shallower water. The bulk of the bedforms have a wavelength from 50 to 200 m.

5.2.4.3. Morpho-dynamical implications

Generally, observations demonstrate that whenever sand is available and the current is strong enough, bedforms can be expected (STRIDE (1982)). Large-scale bedforms seem to form where the tidal ellipse is elongate and where the maximum flood or ebb velocity is greater than the velocity in the perpendicular direction. Under such conditions, the cross flow can have little effect in destroying the bedforms, formed by maximum flood or ebb currents (McCAVE (1971)). Moreover, sizeable bedforms seem only to occur in areas of abundant sediment supply. The more sand becomes available towards the sandbanks, the higher the bedforms can grow. However, they are constraint by wave action.

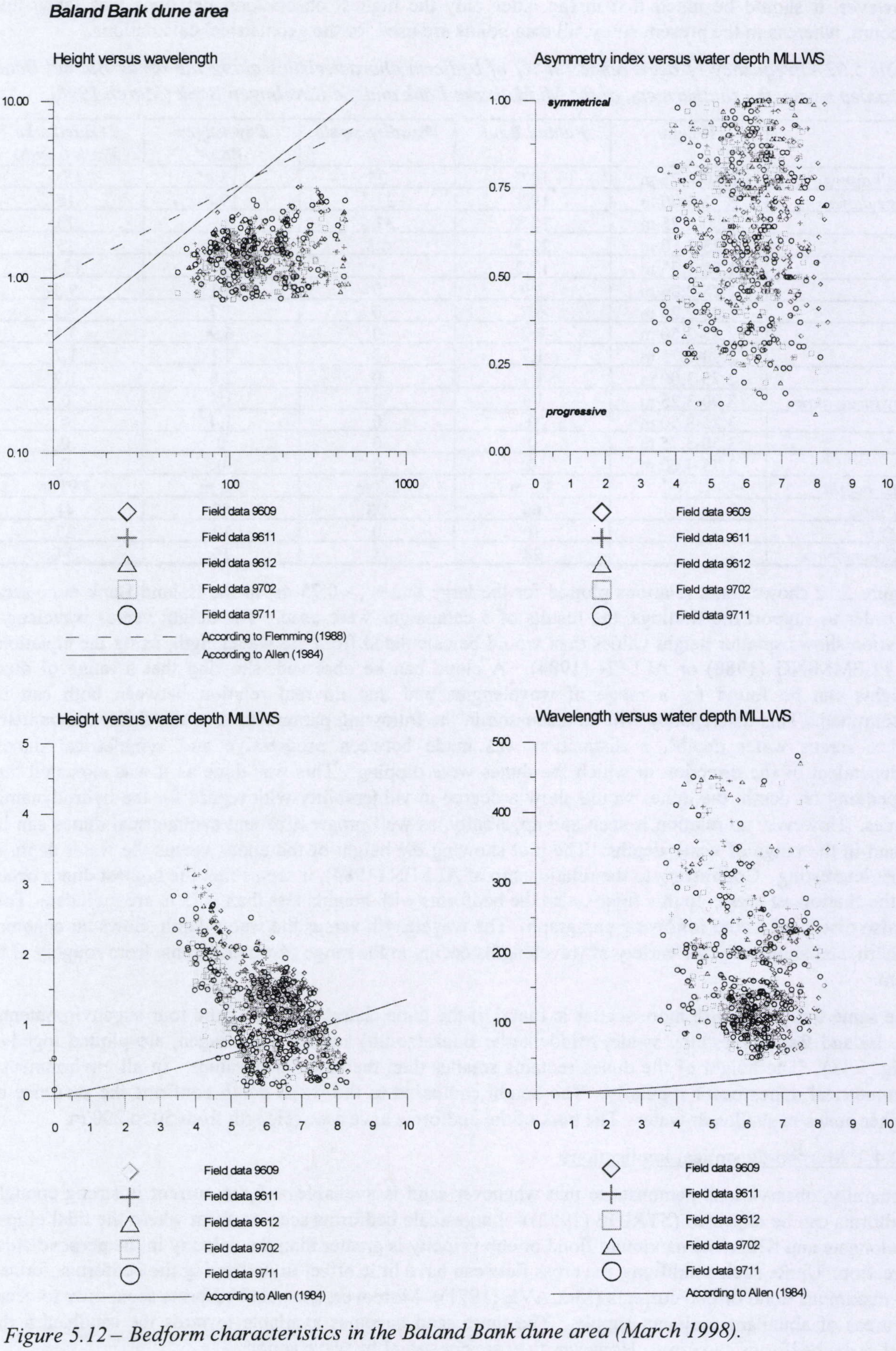


Figure 5.12 – Bedform characteristics in the Baland Bank dune area (March 1998).

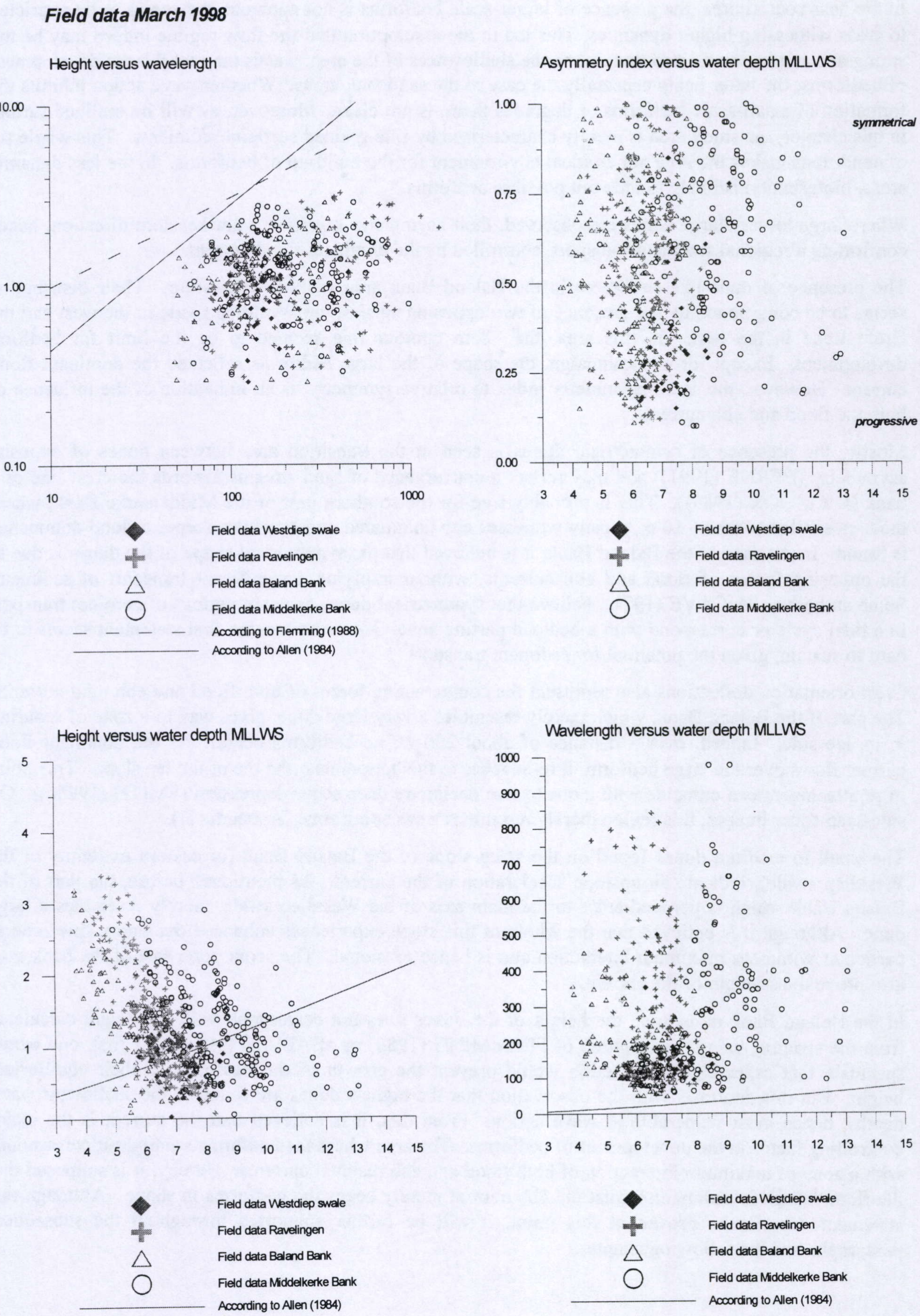


Figure 5.13 – Bedform characteristics of the four subenvironments (March 1998).

In the near coastal area, the presence of larger-scale bedforms is not apparent and seems to be restricted to areas witnessing higher dynamics. This led to the assumption that the flow regime indeed may be too strong at some locations, and that due to the shallowness of the area, waves may inhibit the development of bedforms; the latter being especially the case in the sandbank areas. Whether wave action inhibits the formation of small-scale bedforms or degrades them, is not clear. Moreover, as will be outlined further in this chapter, the study area is mainly characterised by fine-grained surficial sediments. This whole set of conditions makes the area not an ideal environment for the build-up of bedforms. In the less dynamic areas, bioturbation is likely to fade out possible bedforms.

Where large to very large dunes are observed, their asymmetry points in a northeastern direction, hence confirming a regional sediment transport, controlled by the dominant flood current.

The presence of dune-like structures in the Baland Bank area is most interesting. Their distribution seems to be conditioned by the presence of two opposing swales, the Westdiep swale in the west and the Grote Rede in the east. In this area, the - 8 m contour line seemed to be the limit for bedform development. Except for one campaign, the shape of the large bedforms reflected the dominant flood current. However, the small asymmetry index to relative symmetry, is an indication of the influence of both the flood and ebb current.

Mostly, the presence of symmetrical dunes is seen in the transition area between dunes of opposite asymmetry (BERNE (1991)) and may reflect a convergence of sand streams towards the crest line of a bank (DE MOOR (1985)). This is probably true for the southern part of the Middelkerke Bank, where the area shallower than - 10 m, mostly witnesses ebb dominated dunes, whilst deeper a flood dominance is found. In the case of the Baland Bank, it is believed that the symmetrical shape of the dunes is due to the opposing forces of flood and ebb currents, without implying a significant transport of sediment. Some authors as McCAVE (1971), believe that symmetrical dunes occur in regions of zero net transport in a tidal cycle or correspond with a bedload parting zone. Nevertheless, the first statement seems to be hard to sustain, given the potential for sediment transport.

Crest orientation deflections also represent the counteracting forces of both flood and ebb tidal currents. The part of the Baland Bank, which merely resembles a very large dune, gives way to a zone of scouring in its lee side. Indeed, over a distance of about 250 m, no bedforms occur. As the dominant flood current flows over the large bedform, it re-attaches to the bottom near the toe of the lee slope. This point of re-attachment can coincide with a one to two decimetre deep scour depression (SMITH (1988c)). On side-scan sonar images, this region merely resembles a sweeping zone (Appendix B).

The small to medium dunes found on the steep slope of the Baland Bank (or eastern extremity of the Westdiep swale), indicate an upslope acceleration of the current. As mentioned before, the part of the Baland Bank which is perpendicular to the main axis of the Westdiep swale, merely resembles a large dune. Although it is believed that the whole of this slope experiences enhanced dynamics, this zone in particular witnesses maximum interaction and is hence erosional. The scour zone east of the bank may also prove the strength of the current.

In the Baland Bank dune area, the height of the dunes does not correspond with the height calculated from the spacing, using the equation of FLEMMING (1988) or of ALLEN (1984). At first, one would speculate that especially wave action would prevent the growth of the bedforms to their equilibrium height. But this contrasts with the observation that the highest dunes are found in the shallowest water depths, hence most vulnerable to wave action. From this, it is believed that the current is the major controlling factor in the development of bedforms. The area where the bedforms are highest corresponds with a zone of maximum interaction of both flood and ebb residual currents. Hereby, it is supposed that the flood brings in sediment, whilst the ebb current merely keeps the bedforms in shape. Although this statement can not be proven at this point, it will be further supported throughout the subsequent paragraphs and the following chapter.

The discrepancy in the height of the dunes regarding its wavelength, seems to be merely dependent on the estimation of what amount of sediment in transit is associated with bedform propagation. As shown in the previous chapter, most of the sediment is carried in suspension, so normally not taking part in the bedload transport. Indeed, if the height of the dunes is calculated according to the KENNEDY (1969) or VAN RIJN (1984) formulae, which take into account the ratio of bedload versus total load, then the dimensions become much smaller. Using the sediment transport model for the influence of currents alone (Chapter 4), in the Baland Bank dune area a fairly good agreement is found between the dimensions of the dunes in the field and the calculated ones (Table 5.03):

Table 5.03– Results of the sediment transport model "stransv" for currents alone (Chapter 4). The input values correspond to a zone in the Baland Bank dune area, where ADCP measurements were carried out in September 1998.

Input Grain-size: d50: 308 µm, d90: 466 µm, d10: 222 µm Depth: - 7.5 m Depth-averaged current: 0.90 m/s	*Output*	*Field data*
Height of the large dunes	0.71 m	~ 0.40 – 1.13 m
Wavelength of the large dunes	55 m	~ 65 m
Height of the ripples	0.0440 m	
Wavelength of the ripples	0.31 m	
Median suspended diameter	284 µm	
Bedload versus total load	14 %	

Key: The calculations are mainly based on the formulae of VAN RIJN (1984). These take into account a transport parameter, depending on the amount of suspended load.

Still, it should be noted that a high rate of sediment suspension and transport does not necessarily mean that all of the material is bypassed. The amount of suspended sediment may be high along the gentle side of a large dune, but the fallout of that material can also be important on the gently sloping lower part of the forset dune front (McCAVE 1971). This implies that suspension load can contribute to the forward movement of the bedforms.

Interesting is the presence of very small ripple-like features in the most shallow areas (Appendix B). They are thought to be induced by wave action. In general, wave ripples are more symmetrical, rounded and trochoidal in cross-section and have longer and straighter crests with more uniform heights and spacing than current ripples (e.g. ALLEN (1984)). It is thought that the symmetrical, wave formed ripples can be created by wave motion on a day-to-day basis and are likely produced by shoaling waves, generating oscillatory and unidirectional currents (VAN DE MEENE (1994)). However, it should be noted that in the most shallow areas, the bulk of the sediment samples consisted of well-sorted shell fragments. It is not clear to what extend such bioclastics are responsible for the typical texture on the side-scan sonar map (Appendix B).

Due to their limited dimensions and the dependency of the quality of side-scan sonar imagery, small to medium dunes are difficult to recognise in the field. Where they are found, they are supposed to indicate local accelerations of the current, but their importance as sediment transport indicators remains rather vague. Although they predominantly point in a northeastern direction, it seems likely that their shape can be altered by the ebbing tide. In contrast to the offshore very large dunes, no pronounced compound dunes were apparent in the near coastal area. It is observed that most sediment is transported as suspension load, hence not taking part in the build-up of bedforms. Where small to medium dunes are present, the variation in height may be attributed to local accelerations and decelerations of the flow over the larger bedforms (TERWINDT (1971)). In that case, sediment transport is presumably steered by the migration of the small-scale features, superimposed on the large-scale bedforms. The latter hence act as a platform.

From the echosoundings, no bedforms were observed that indicate a sediment transport pathway from the Stroombank to the Baland Bank. Therefore, it can not be proven that the Stroombank acts as a local source for the Baland Bank. The berm-like morphology connecting both sandbanks, merely represents a piling up of sand due to a convergence of both flood and ebb residual currents. However, the main driving agent is the flood current, which is locally enhanced by the Coriolis force. Also BASTIN (1974) put forward this effect to explain a difference in dynamics along both sides of a channel. In this perspective, a change in water level is induced perpendicular to the current direction. This means that the right side of a channel experiences higher water pressures, especially when water levels are high. Moreover the wave height is subjected to exponential changes along both sides of a channel, hence reinforcing sediment transport during the flooding tide.

Also, the bedforms found along the Westdiep swale, can be seen in that perspective. Moreover, their occurrence seems to align with the narrowest part of the swale and no correlation could be found with bedforms observed on the Stroombank. This proved that this zone of higher dynamics, along a stretch of about 1600 m, is due to acceleration effects along the slope of the Westdiep swale towards the bank, and thus locally generated. Once out of the zone of maximum shear stress, no more bedforms are detected.

Due to the shallowness of the area preventing measurements during the ebbing tide, the importance of ebb-dominated currents could not be fully established. Bedforms witnessing the counteracting of the ebb during the flood, are rare, but do exist. This only confirms that these forces should not be underestimated. This phenomenon shall be discussed in more detail in the following chapter,

In general, the interaction zone of the near coastal area and the Flemish Banks is characterised by the presence of well-defined bedforms. In particular, the southern end of the Middelkerke Bank and the Ravelingen area were investigated. This enables to compare bedform dynamics in the offshore and nearshore areas, helping in the understanding of offshore – onshore sediment fluxes. Along the shallowest part of the Middelkerke Bank, the influence of the ebb residual current, as also evident in the Flemish Bank area, can not be ignored. Interesting is the asymmetry of the bedforms located deeper than - 10 m, as this corresponds to the observations in the near coastal area. Although the dimensions of the dunes are fairly high in water depths of - 10 to - 11 m, they quickly die out towards the Westdiep swale. It is not clear whether this is solely due to a difference in current characteristics or also to a limited availability of sand. Along the Ravelingen, the whole area seems to be flood dominated, though ebb caps can be observed towards the north.

Although only observed offshore, it is plausible that only the crest flips over during the ebbing tide. From all the observations, it can be concluded that the larger dunes are not reversed during the tidal cycle, meaning that a change in morphology is due to the lunar cycle (spring or neap tide) and/or external controls.

Tidal influence

In any study on bedform dynamics, the time of surveying regarding the tidal cycle, is an essential element in the discussion whether the asymmetry of the bedforms can be used as an indicator of residual sediment transport or not. Some references are given in paragraph 5.2.1. Especially in shallow water environments, it can be suspected that both flood and ebb tidal currents are competent enough to change the asymmetry of the bedforms. In the present investigation, the areas were surveyed in similar time periods regarding the tidal cycle. Moreover, given the draught of the research vessel, the different environments were always sailed in a specific window of the tidal cycle. The surveys in the Baland Bank area were restricted to a time span of three before up to four hours after high water; the same applies to the Ravelingen area. The southern part of the Middelkerke Bank and the Westdiep swale were the low water alternatives. As mentioned before, the dunes in the Westdiep swale and the ones in the Baland Bank area mostly pointed in a northeastern direction (table 5.02), except for one campaign where all dunes had a reversed asymmetry, regardless of the flooding tide. Figure 6.09 in the following chapter demonstrates that the whole body of the dune was reversed to the adverse conditions, not merely showing an ebb cap as would be more likely, given the adjustment time needed to accomplish such a change in morphology. It seems possible that the smaller dunes reverse their asymmetry during the tidal cycle. In the southern part of the Middelkerke Bank, the difference in asymmetry along the dune crests is not related to the phase of the tidal cycle during surveying (O'SULLIVAN (1997)). Also in the Ravelingen area, no correlation could be found between the asymmetry differences along the dune crests and the tidal cycle (DELGADO BLANCO (1998)). Although the dune field to the north of the Ravelingen sometimes witnessed an ebb cap morphology, the main body of the structures remained flood dominant.

5.2.5. A bedform distribution map and inferred bedload transport pathways – synthesis and discussion

From the morphology and the bedform evidence presented in the previous paragraph, some deduction can be made of sediment transport pathways in the near coastal area.

The results of the sediment transport modelling outlined in Chapter 4, already gave an indication, that the potential for sediment movement is primarily in a northeastern direction; this corresponds with the dominant flood residual current. Although ebb peak velocities are on average 39 % smaller than those during the flooding tide, table 4.03 and 4.04 demonstrate its potential for sediment motion during some stages of the tide.

As was expected from the calculations in Chapter 4, the Westdiep swale has a major influence on the dynamical characteristics of the sandbank – swale system. Up-climbing ripples were regularly observed along its slope, and even dune-like features could be sounded along the western extremities of the two major sandbanks. These areas of higher dynamics correspond with the head of the banks; this confirms an input of sediment to the sandbank system, as was hypothesised by CASTON (1981). Indeed, it seems plausible that the presence of the larger scale bedforms is also a reflection of the availability of sand, suggesting there is a continuous balance of sand supply and hydrodynamics.

Also along the shoreface, up-climbing ripples are found. However, from the step-like morphology of the shoreface more to the west, it is thought that significant sediment transport is restricted along this plateau (Fig. 5.01), and merely operates in a longitudinal sense.

Due to the rather undifferentiated nature of the morphology of the Stroombank and the Nieuwpoort Bank in general, there is no evidence of a sand circulation around the banks. Bedforms, having a different asymmetry along both sides of the bank have not been observed. It should be noted that only a limited part of those banks has been acoustically investigated. But from the numerous samplings and the boxcoring campaign of July 1994, it seems likely that bedform growth is inhibited by wave action. Moreover, the amount of suspended load strongly exceeds the amount of sediment transported as bedload. Taken into account the potential of sediment transport in this area, those banks seem to be in a dynamic equilibrium, at least on a short term.

The tide-topography interaction over sandbanks has been examined by YANG (1998) using a 3D mathematical model, including the hydrodynamical interaction between two parallel sandbanks. From this, the current ellipses on the two sandbanks seem to differ only slightly, but the current ellipses in the channel between the sandbanks are more rectified than on the other side of the banks. Except for the residual current in the channel, the circulation for each sandbank can be considered as almost independent.

Compared, to the field observations, Figures 5.14 and 5.15 can partly be supported. Although as mentioned before, no statement can be made concerning a circulation around the banks, morphological evidence does confirm higher sediment dynamics along the western part of the Stroombank, which was already attributed to the Coriolis force. In contrast to the field observations, a small residual current is calculated at the southwestern extremity of the sandbanks. The echosoundings do show pronounced up-climbing dunes in those regions, and it is supposed that sand enters the sandbank system at the broader heads of the banks. The current meter data in the interaction zone between the Nieuwpoort Bank and the Stroombank, showed a enhanced effect of the flood current up to 2 hrs more, than would be expected from neighbouring current meter stations (Fig. 4.04). This means that the current ellipses in such environments are indeed rectified by the banks. This was also observed by STOLK (1993a) along the Middelkerke Bank. The ebb residual current along the steep side of the banks can not be demonstrated. It should be noted that YANG's calculations were performed for two elliptical sandbanks having an angle (θ) to the coast of 20° and contoured by the - 20 m isobath; this contrasts to an angle of 3.5° to 7.5° and a - 5 m isobath, contouring the sandbanks in the study area.

From the asymmetry of the large-scale bedforms, it is clear that the flood current mainly controls the residual sediment transport on the Baland Bank. However, the shape of the sandbank towards the south

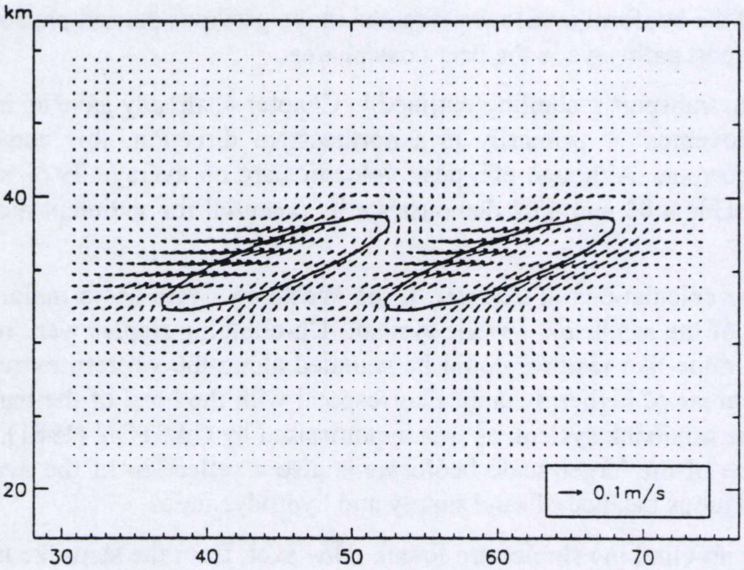


Figure 5.14 – The depth-averaged residual current for two elliptical sandbanks with θ = 20°. The - 20 m isobaths are shown by solid ellipses (YANG (1998)).

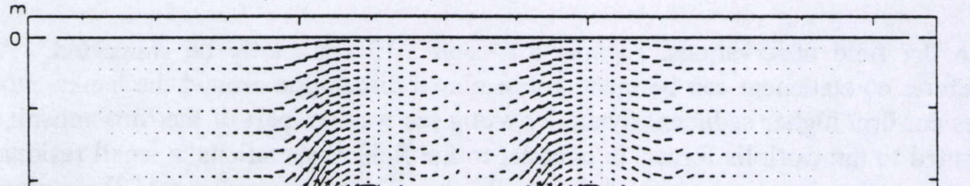


Figure 5.15 – The vertical residual current for two elliptical sandbanks with θ = 20° (YANG 1998).

seems to be influenced by ebb residual forces. This part of the bank is indeed aligned with the Grote Rede swale.

More or less, the same morphological structure is found in the Ravelingen area. To the north, the sandbank is shaped by the flood, whilst towards the south, ebb residual forces seem to have shaped the bank, although the bedforms merely point in a northeastern direction. However, due to the more offshore position of the sandbank it is not surprising that the bank is more influenced by the ebbing tide.

Finally, the southern part of the Middelkerke Bank, clearly reflects the difference in dynamics between the offshore Flemish Banks and the near coastal area. In water depths shallower, than - 10 m, the dune-like structures tend to dip in a southwestern direction, whilst flood-dominated dunes are found in deeper water. More or less symmetrical dunes occur in the middle. Although, the flood current also dominates the Flemish Bank region, the ratio of the flood peak tidal current velocity against the ebb peak tidal current velocity is only 1.11. In the near coastal area, a value of 1.43 to 2 is calculated (LANCKNEUS et al. (1994)). Still, on the basis of the asymmetry of larger dunes, the eastern, landward flank of the Flemish Banks is mostly dominated by ebb residual currents (i.e. STRIDE (1982); DE MOOR (1985); VLAEMINCK et al. (1989); HOUTHUYS (1990); LANCKNEUS et al. (1994)).

A compilation of the observations and interpretations is given in Figure 5.16.

On the map, the presence of trawl marks (i.e. north of the Nieuwpoort Bank) is also shown. Those marks represent parallel lines that are 15 to 20 m apart. On the sonographs, they appear as light tones suggesting that they are more or less 2 m wide grooves or localised depressions, partially infilled with unconsolidated sediments. The presence of the marks could indicate zones of lesser dynamics, as active processes normally would wipe them out, though they may also be observed in swales, actively shaped by the flood current, as shown in Figure 5.09.

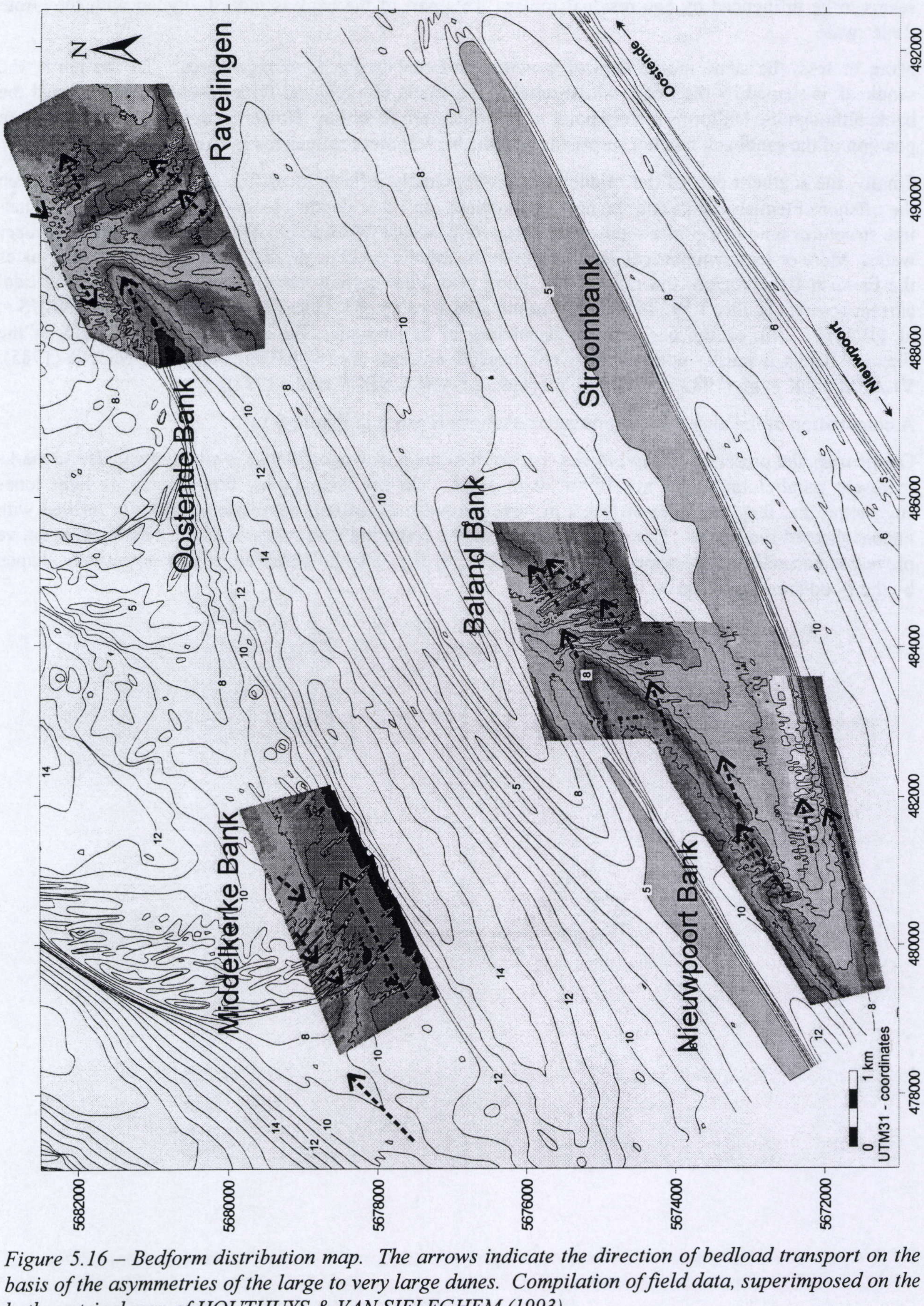


Figure 5.16 – Bedform distribution map. The arrows indicate the direction of bedload transport on the basis of the asymmetries of the large to very large dunes. Compilation of field data, superimposed on the bathymetrical map of HOUTHUYS & VAN SIELEGHEM (1993).

5.3. Sedimentological response of the sea bed

5.3.1. Introduction and previous work

The sedimentological characteristics of the Belgian coastal zone have been studied by a variety of investigators, though only a few focussed on the near coastal area. BASTIN (1974) gives an overview of the history of the lithological mapping, together with the most important maps, available at that time. However noteworthy is the nautical map of STESSELS (1866), as this map gives already an indication of the surficial sediments.

Table 5.04– The main sedimentological characteristics shown on the map of STESSELS (1866).

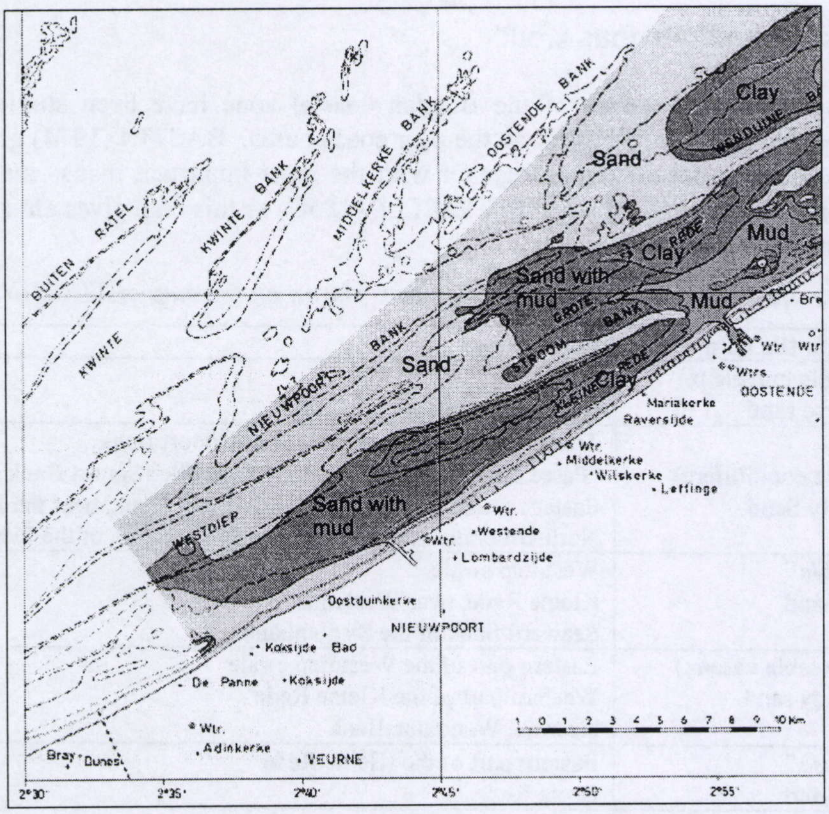
Indication on the map	Localisation
"*S. grav.*" (sable graveleux) => Coarse sand	North of the Wenduine Bank
"*S. coq.*" (sable coquillifère) => Shelly Sand	Transition Westdiep swale – Nieuwpoort Bank "Passe du nord-est", interaction zone Nieuwpoort Bank – Stroombank Eastern prolongation of the Nieuwpoort Bank, near the Ravelingen area Northern branch of the Westdiep swale, south of the Flemish Banks
"*Sable*" => Sand	Westdiep swale Kleine Rede, near Westende Seaward flank of the Stroombank
"*S. vaseuse*" (sable vaseux) => Muddy sand	Eastern part of the Westdiep swale Western part of the Kleine Rede Near the Wenduine Bank
"*Vase*" => Mud	Eastern part of the Kleine Rede Grote Rede
"*V. noire*" (vase noire) => Mud (black)	Swale, east of the Oostende Bank

Primarily, the unconsolidated sediments consist of terrigenous quartz sand, which can be locally enriched by either mud or bioclastic elements. This quartz sand dominates and is generally fine-grained and moderately to well sorted with a low carbonate content. The sediment is the surficial expression of the Holocene sand prism (GULLENTOPS et al. (1977)).

The work of BASTIN (1974) can be regarded a reference work for the sedimentological characterisation of the Belgian near coastal area. Based on the natural radioactivity of surficial sediments (^{40}K) (clays versus quartz sands with a small amount of ^{40}K-bearing feldspar grains) and calibrated with a set of 240 bottom samples, BASTIN was able to draw a lithological map of the Belgian near coastal zone and the Schelde estuary (Fig. 5.17A, B). Due to the nature of the technique, continuous measurements could be performed, and as the results could be interpreted in function of rigidity and density, recent sedimentation patterns of mud could be distinguished. In that sense, the map of BASTIN is more a structural map than a map purely representing grain-sizes. As the measurements were performed in June-July/August of 1964, it should be kept in mind that the observations are likely to reflect calm weather conditions. The profiles were sailed transversally to the coast and were spread 500 to 1000 m apart. The offshore limit was determined by the extent of the heterogeneous distribution of the surficial sediments, roughly extending 13 km offshore.

West of Oostende, the lithological map of Bastin shows a less complex sediment distribution pattern as along the East Coast. In general, sand characterises the offshore area off Nieuwpoort – Oostende. Clay is evident along a narrow strip in the nearshore area and just south of the Stroombank. Pure mud seems to appear locally in some spots south of the Stroombank, Kleine Rede and offshore Oostende. Sand and mud have an important distribution pattern, but seem to be merely confined to the swales Grote Rede and Kleine Rede. Based on the grain-size analysis of 240 bottom samples and relying on his experience in the area, BASTIN also compiled a grain-size map (Fig. 5.17B). The indices are an indication of the grain-size and the sorting of the sediment. Areas having more than 50 % of the fraction less than 62 µm are indicated separately. Well-sorted fine sands having an index of 333 (two quartiles and the median are within the range of 125-250 µm) seemed to be dominant throughout the coastal area (54 %).

A



B

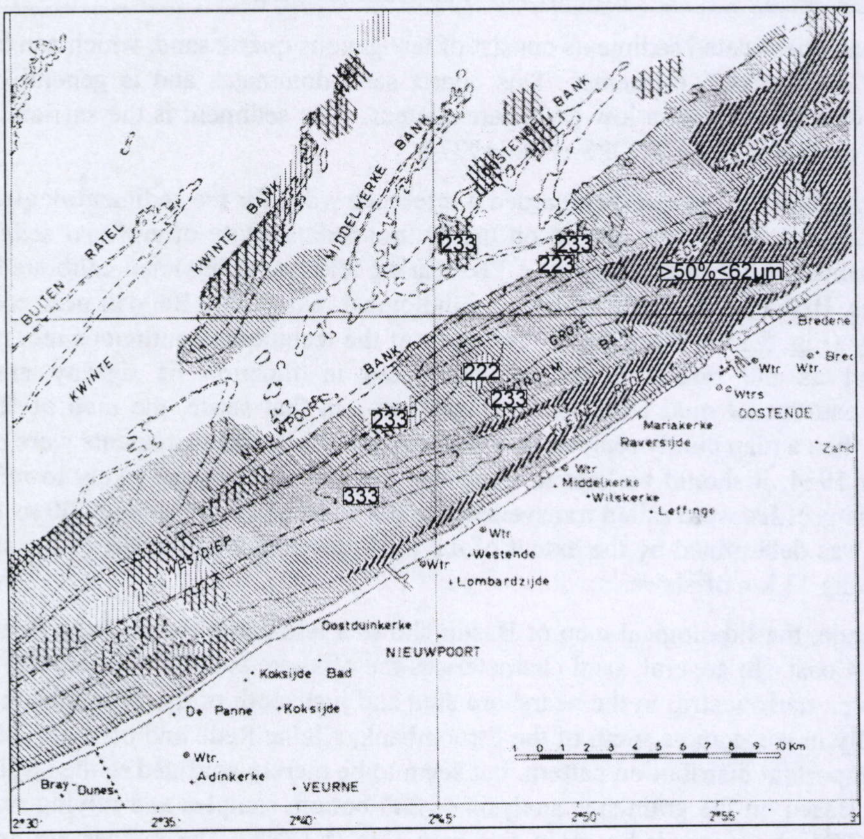


Figure 5.17 – A. Lithological map of the Belgian coastal zone; B. Grain-size map (BASTIN 1974). (2: 500-250 µm; 3: 250-125 µm; 4: 125-63 µm)

Due to the occurrence of Tertiary and Quaternary clay, which can be eroded by the hydrodynamical agents, it is of paramount importance to clearly define the term "mud". In this context, mud should be regarded as a loosely compacted mixture of clay minerals (< 2 µm), silt (2 - 63 µm), sand (> 63 µm), and colloids (1000 - 1 µm), added with variable amounts of organic matter (0 - 5 volume %) and carbonate minerals (15 - 35 volume %) (BASTIN (1974); MALHERBE et al. (1982)). The organic and Fe-colloids are the binding agent of non-colloidal particles, especially when flocs are formed (i.e. during slack water). Clay minerals are essential, but do not have to be the major constituent. Sandy and silty quartz minerals can be abundant, even up to 30 % without an important change in cohesion strength or rigidity. A water content of 150 to 200 %, partly the amount of organic matter and flocculated constituents, give a loosely compacted structure. The continuous character of the muddy deposits, resulting in a fairly constant physical behaviour, is due the binding of the flocs or particles by water molecules. Once these are broken (i.e. dewatering), a different behaviour is apparent. When the muddy sediments are desaggregated and their organic material oxidised during the drying phase, the sediment can be described as a clayey silt, sandy clay or clay.

Usually, mud deposits are associated with reducing conditions. Organic matter is decayed by bacterial activity to minerals and gases (CH_4, H_2S, CO_2, ...). During calm conditions, the redox potential (Eh = 0-surface) remains at the interface seawater-bottom; after winter storms the enhanced oxidation puts the Eh = 0-surface to 3 - 20 cm below this interface (MALHERBE et al. (1982)). Flocs are characterised by a very low specific weight, but a relative large diameter. MALHERBE et al. (1982) determined the size of those flocs by means of a decantation-tank and suspension-tracers. For flocs formed during slack water, a diameter of 10 - 30 µm was reached. During the flood and ebbing phase of the tide, turbulence is likely to hold the mud aggregates in suspension. Mud deposits consolidate rather slowly. Loose mud deposits in areas of high mud sedimentation show a slow increase in density with depth and a slow consolidation speed, as the relatively high initial concentration slows down the settlements and the consolidation process (MALHERBE et al. (1982)).

An interesting feature is the mud plume in front of the Belgian coast (Chapter 2). Due to the lower rigidity of the mud, sand in transport can be trapped. The muddy fraction is deposited in the centre of those plumes, whilst sandy sediments are trapped along its borders (BASTIN (1974)). Very high concentrations and rigidities of the mud allows sand and even fine gravel to trespass the muddy seafloor, allowing an offshore-onshore exchange of sediments. However, already BASTIN (1974) mentioned that such an exchange becomes more difficult, as the intensive dredging and dumping works at sea are likely to diminish the rigidity of the mud.

Out of the analysis of Bastin, it might be deduced that sand and mud (also composed of a significant amount of sand) are in transport. Both can be deposited simultaneously, but in more dynamic areas the sand will settle out, whilst the fines are carried away with the current. However, the substratum remains the most likely source for fine-grained sediments.

Since the work of BASTIN (1974), sedimentological maps have been drawn, but only for internal purposes (MINISTERIE VAN OPENBARE WERKEN (1976-1982); MINISTERIE VAN OPENBARE WERKEN (1984-1986)). CEULENEER & LAUWAERT (1987) and BALSON et al. (1991) provided a synthesis of the available data. The sedimentological maps confirm the uniform distribution of sand for the offshore area, apart from some outcrops of Tertiary clay layers (Ypresian, Rupelian). More to the coast, the surficial sediments are finer-grained and locally enriched with mud. The grain-size distribution is likely to be complex and variable. It should be noted that although the fraction less than 63 µm only amounts 0-3 % on the Belgian continental shelf, those values can easily reach more than 50 % within the harbours (i.e. Oostende 42-88 %) and navigation channels (i.e. Oostende 0-49 %). In general, it is stated that fine sands (d_{50}: 175-250 µm), likely enriched with mud, are distributed between 0 and - 12 m water depth (MLLWS). Medium-grained sands (d_{50}: 250-500 µm) are commonly found at depths exceeding - 12 m (MINISTERIE VAN DE VLAAMSE GEMEENSCHAP (1994)).

DE MAEYER & WARTEL (1988) discussed the relation between the superficial sediment grain-size and the coastal sandbanks. They indicated unimodal to bimodal fine sandy sediments for the banks and foreshore, and a mixture of sediments (up to 20 % < 200 µm) in the swales. However, they do not provide for a sedimentological map.

Within the MASTII project STARFISH, a sedimentological investigation was carried out in the near coastal area on the basis of a detailed set of boxcores. As stated previously, it was made possible to discuss some of the boxcores in the present thesis.

From the conducted studies and literature, it can be concluded that in general the near coastal zone is characterised by a heterogeneous mixture of sediments. Although the sandy sediments are classified as being fine-grained, the grain-size distribution pattern is biased by possible enrichments of mud. Moreover, those sediments are lying discordant on a heterogeneous Tertiary substrate. Locally those older sediments can be eroded, which makes it hard to unravel the origin of the sediments and their distribution. All those factors render it rather difficult to relate differences in grain-size to the ruling hydrodynamic agents. Indeed, as indicated in the previous chapter, it is not straightforward to correlate the observed strong tidal currents and wave action with rather fine sandy sediments, in an area shallower than - 15 m.

The grain-size distribution of seafloor sediments has important implications for diverse aspects of sediment dynamics, especially for the modelisation of sediment transport. In the framework of this study, emphasis is put on the characterisation of the surficial sediments of the most dynamic areas. As outlined above, past sampling strategies concentrated on the coastal zone as a whole and did not clearly differentiate between depositional environments. Therefore, it is difficult to unravel the spatial and temporal variability of those seabed grain-size distributions.

The relationship between the spatial variation of the properties of the sea floor sediments and the acoustic backscatter from the surface of the sea floor is investigated using boxcores, surficial sediment grab samples and side-scan sonar data. Acoustic backscatter strength has a high, direct correlation with the mean grain-size of the sediments, and is correlated to the carbonate content of the sediments, particularly in medium and coarse sand facies (DAVIS et al. (1996)).

5.3.2. Sampling strategy

Boxcoring

The sedimentary structures at and directly below the seabed were studied using a Reineck type boxcorer. Details on the use and further processing of the boxcores were described in Chapter 3.

The boxcores recovered onboard the "*Navicula*" (July 1994), were taken along 4 transects perpendicular to the shore. As to reveal the spatial variability, boxcores were taken at depth contour intervals of 1 m. The ones obtained onboard the "Belgica" date from November 1996 and February 1998. The November boxcores were taken in the Baland Bank area. The aim of the February boxcores was to verify a seismic section, comprising the sandbank – swale system in a transversal direction.

Table 5.05– Overview of the boxcoring campaigns.

Research vessel	Reference	Tidal phase	Details
Navicula	9407	Mid tide	123 boxcores along 4 profiles, transversal to the coast
Belgica	9611	Spring tide	4 boxcores along the Baland Bank
Belgica	9802	2 days before neap tide	10 boxcores along rG20-21

Key: the reference is composed of the year and month of sampling (YYMM);

The MB9407 dataset represents fair-weather circumstances. The November 1996 boxcores were taken after a stormy period of 8-10 Bft SW-NW winds. The February 1998 boxcores were retrieved following a relatively calm period. The main goal of the boxcoring campaigns was to unravel the vertical and spatial heterogeneity of the seafloor and to determine the tidal versus wave dominance over the area.

Analogous research has been described by HOWARD & REINECK (1972); REINECK (1976); HOUTHUYS (1990); STOLK (1993b) and VAN DE MEENE (1994).

Grab sampling

Given the scope of the present study to investigate sediment and morphodynamics in a coastal system, emphasis was put on the differentiation of grain-sizes in the most dynamic areas. However, in order to distinguish those zones and to situate them in a global sediment-dynamical framework, the whole area was sedimentologically characterised during the December 1995 campaign and only sporadically afterwards. Moreover the detailed set of boxcores provided already a good framework for subsequent investigations.

The finer-grained environments were avoided, as it is very difficult to statistically examine grain-size distributions. They are too sensitive to random variables to be linked with hydrodynamical and meteorological conditions. Moreover, those areas are spatially also too heterogeneous, meaning that positioning or sampling errors could lead to significantly different results.

The major sandbanks Nieuwpoort Bank and Stroombank were monthly sampled in the period 1995–1996 and seasonally in 1997 and 1998. The stations were chosen according to their morphological position along the banks. As well longitudinal as transversal trends in grain-size variation were taken into consideration. The "*Belgica*" campaigns concentrated on the morphodynamically interesting zones: Westdiep swale, Baland Bank, Ravelingen and the southern part of the Middelkerke Bank. Within these areas, samples were taken in a grid and attention was paid to restrict the sampling to one morphological entity and thus not to mix environments. Table 5.06 gives an overview of the samples taken throughout this study. Note that the samplings taken with the "Oostende XI" / "Jacqueline" are excluded (see Table 6.02).

Table 5.06– Overview of the sampling campaigns (Van Veen grab samples).

BELGICA campaigns	Baland Bank	Ravelingen	Middelkerke Bank (south)	Westdiep	Extra
9512					40 samples NCA
9602	11	7	21		
9605				26	12 samples along the - 6 m line (shoreface)
9609					12 samples along the - 6 m line (shoreface)
9611	20		15		
9705	40				
9709		30			
9806					Samples current meter stations

Key: the campaign reference is composed of the year and month of sampling (YYMM); NCA: near coastal area. The numbers correspond with the amount of samples taken.

The hydrodynamical and meteorological conditions preceding and during the sampling campaigns are taken into consideration, but will be presented in the following chapter.

5.3.3. Sedimentary sequences revealed by boxcoring

5.3.3.1. Characterisation of the different facies in the near coastal area

Sedimentary sequences along a transversal profile comprising the Oostende Bank – northern branch of the Westdiep swale – the eastern prolongation of the Nieuwpoort Bank – Grote Rede swale – Stroombank – Kleine Rede swale – shoreface – beach (Fig. 5.18)

The Oostende Bank sedimentary facies is characterised by an abundance of shelly material and coarse sands, that often witnesses cross-bedding (Fig. 5.18, boxcore 284). The amount of shells decreases gradually towards the coast, though the transition to the northern branch of the Westdiep swale still consists of a fair amount of shelly material. As the depth increases, the sedimentary pattern becomes more and more reduced. Along the slope, boxcores demonstrate a coarsening upward sequence. In the deepest part of the swale, a dense amount of *Lanice conchilega* occurs on top of a matrix, consisting of coarser sands and shelly material. The sediments are highly reduced.

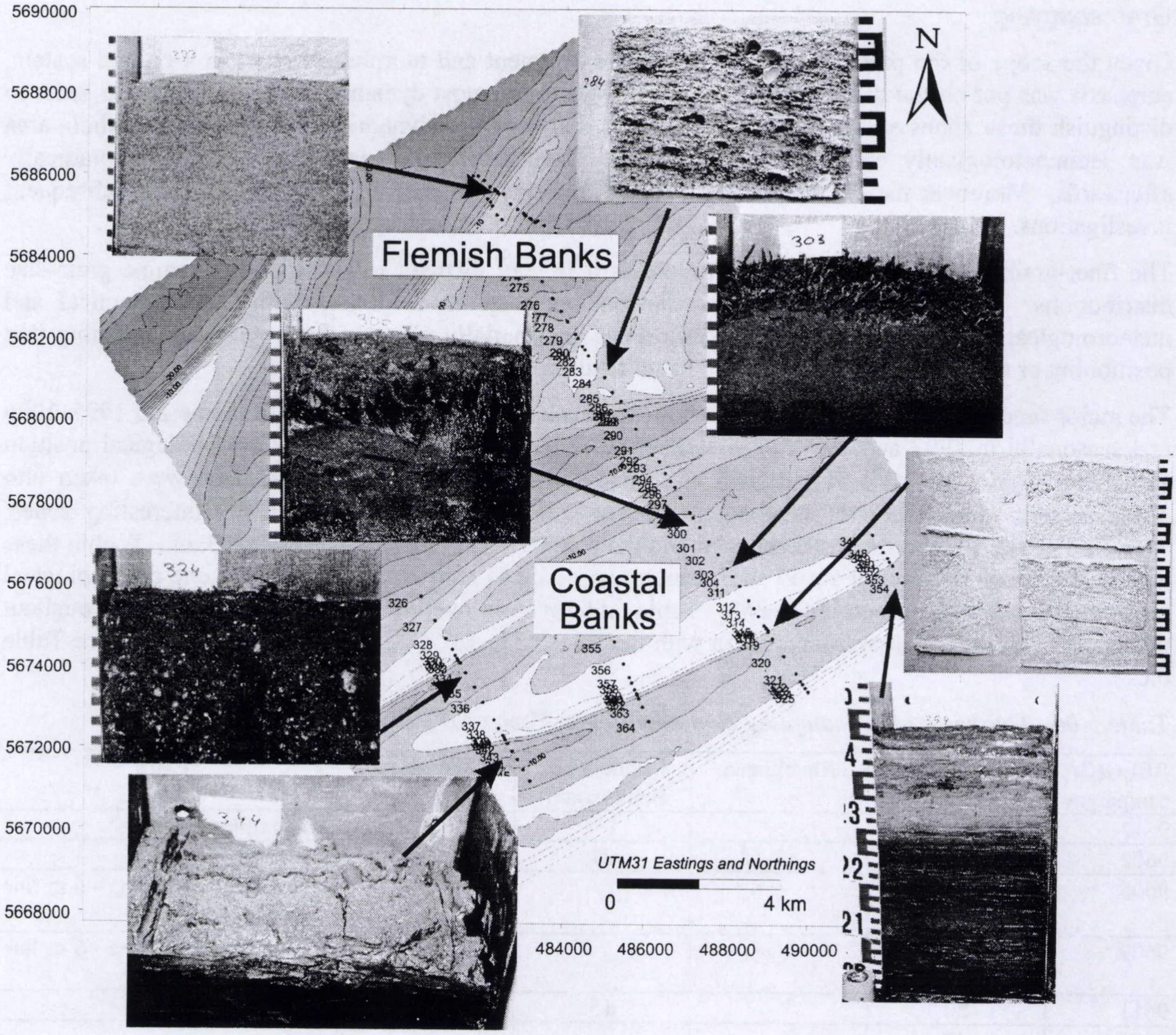


Figure 5.18 – Boxcores representative of the sedimentary facies in the near coastal area.

The landward flank of this swale and the eastern prolongation of the Nieuwpoort Bank consist of a fine sandy matrix with only a minor amount of shells. The reduction rate decreases with shallowing depths. *Echinocardium cordatum* and *Lanice conchilega* are the main faunal components. The deepest part of the Grote Rede swale is characterised by an important admixture of clayey sediments. The matrix consists of fine to very fine sands and is fully reduced. *Lanice conchilega* can be present (Fig. 5.18, boxcore 300). Towards the Stroombank, clay intercalated into a fine sandy matrix, remains visible as is the high reduction rate and the presence of *Lanice conchilega* in the upper few cms. Mud is also characteristic for this environment. From a depth of - 7 to - 6 m, the sedimentary pattern becomes more and more homogeneous (Fig. 5.18, boxcore 303). Vertically, some coarsening upward sequences can be distinguished. The top of the bank and the upper steep slope are characterised by a homogenised fine sandy matrix (Fig. 5.18, boxcores 315, 316). Some layering is remarked. A small veneer of clay can be intercalated. However, the steep slope of the Stroombank is most peculiar. Although the upper sediments are coarser, the underlying matrix consists of finer sands, intercalated with clay. Reduction is common. At the foot of the steep slope, clayey sediments become more and more important. In the deepest part of the Kleine Rede, clay characterises the sedimentary pattern (analoguous to Fig. 5.18, boxcore 354). However, the upper cm consists of a small veneer of sand. Towards the shoreface, clay remains intercalated in the fine sandy and reduced matrix. Again, from a depth of - 7 to - 6 m, a more homogeneous pattern can be observed, though somewhat deeper lying clayey layers remain present up to a depth of - 4 m. *Lanice conchilega* is present in the strongly reduced fine sandy matrix. Only at depths, shallower than - 3 m, the sedimentary pattern is completely homogenised.

Sedimentary sequences along a transversal profile comprising the eastern extremity of the Stroombank - Kleine Rede swale

The sedimentary pattern along the eastern extremity of the Stroombank is generally finer in texture, and moderately to highly reduced. Clayey layers are intercalated in a fine sandy matrix. *Lanice conchilega* is present, especially along the gentle slope. The latter is also characterised by fining upward sequences. Still, some sedimentary sequences in the shallower areas show some layering. Again, the steep slope is most peculiar: coarse shelly material is found, but on top of a complete clayey matrix. In the deepest part of the Kleine Rede, only a small veneer of sand is observed on top of a clayey facies (Fig. 5.18, boxcore 354).

Sedimentary sequences along a transversal profile comprising the Grote Rede swale – Stroombank (central part) – Kleine Rede swale

Along the central part of the Stroombank, the gentle slope witnesses a much more dynamic sedimentary pattern than along its eastern extremity. Already at a depth of - 8 m, a homogeneous, actively sorted sequence is observed. Only a minor reduction is apparent. The sedimentary pattern becomes more homogenised from the slope to the top of the bank. Again, a coarser texture of the surficial sediments can be observed on the steep slope; these overlie a matrix, which is intercalated with clay. In the deepest part of the Kleine Rede, a complete clayey sedimentary facies is found, but at the top, fresh muddy deposits are seen (Fig. 5.18, boxcore 344).

Sedimentary sequences along a transversal profile comprising the northern branch of the Westdiep swale – Nieuwpoort Bank – Westdiep swale – Stroombank – Kleine Rede swale

The transition of the northern Westdiep swale to the gentle slope of the Nieuwpoort Bank is characterised by a fine sandy matrix, which is highly to moderately reduced. From a depth of - 6 m, coarsening upward sequences can be observed. Although the sedimentary pattern fairly homogenised and only sporadically present, a faint layering can be seen. The surficial sediments of the steep slope of the Nieuwpoort Bank are somewhat coarser. A boxcore in the deepest part of the Westdiep swale showed an abundance of shelly material, though the sedimentary facies is slightly reduced (Fig. 5.18, boxcore 334). The transition with the Stroombank is slightly to moderately reduced. Even a veneer of clay can be observed around a depth of - 6 m. Along the Stroombank, a fairly homogeneous sedimentary pattern is present, except of some layering towards the top of the bank. On the steep slope, shell grit is apparent, as is the presence of coarsening upward sequences. From a depth of - 7 m, the presence of intercalated clay becomes more and more obvious and forms the major constituent, at depths deeper than - 9 m. Freshly deposited mud is observed at the foot of the steep slope (Fig. 5.18, boxcore 344). Deeper, *Spisula subtruncata* is seen on top of the clayey matrix. Towards the shoreface, clay becomes less abundant; more shells are present and some coarsening upward sequences are observed.

Sedimentary sequences along a transversal profile comprising the southern part of the Middelkerke Bank – northern branch of the Westdiep swale - the eastern prolongation of the Nieuwpoort Bank – Grote Rede swale (N) – Baland Bank – Grote Rede (S) and Stroombank

In February 1998, 10 boxcores were taken along a transversal profile, covering the sandbank – swale system, to validate a seismic section. They are represented in Figure 6.39.

The sedimentary sequences are clearly differentiated along the profile. Boxcores along the plateau-like morphology of the southern part of the Middelkerke Bank were mainly built up of fine sands. The reduction level in boxcore 2 was perceived at 15 cm from the top (black mark). *Spisula subtruncata* characterised the upper cms. The sedimentary sequences in the northern branch of the Westdiep swale (boxcores 3-5) were most peculiar. The top levels were fine-grained and enriched in mud, though underneath a mixture of sediments was found, comprising as well coarse sands, shells, shell grit as a pebble and fine-grained material. In boxcore 4, grey sands were observed at 23 cm from the surface. The same holds true for boxcore 5, although clay deposits were found deeper than about 21 cm. The top level of the eastern prolongation of the Nieuwpoort Bank (- 5.5 m) clearly demonstrated well sorted fine to medium sands. On the contrary, the Grote Rede swale was enriched with mud and had a much finer sandy matrix. Although not clearly visible from Figure 6.39, the sediments of the Baland Bank had a much coarser texture and were very well sorted. The sedimentary sequence was completely homogenised. The southern branch of the Grote Rede swale was at this location also somewhat enriched with mud, though the matrix consisted of fine sandy sediments. A reduction level was perceived at 17 cm. Boxcore 10 at the foot of the gentle slope of the Stroombank consisted of fine sandy sediments, slightly reduced towards the base. *Ensis ensis* could be observed. The geological relevance of the boxcores will be discussed in the following chapter.

Sedimentary sequences along the Baland Bank area

Although the Baland Bank dune area is characterised by medium sand and witnesses higher dynamics (Section 5.2.3), it is difficult to find evidence of cross-bedded laminations or layering in general. The boxcores taken in November 1996, as well as the ones taken in February 1998, represent a sedimentary sequence that consists completely of homogenised coarser sands.

5.3.3.2. Sediment-dynamical implications

From the description given above, it seems difficult to find sedimentary sequences that are not being disturbed. The boxcores showed that the swales are generally bioturbated inhibiting the formation of, or fading out, possible structures. In the vicinity of and on the sandbanks, the sediment texture becomes more homogenised and bedform development seems to be inhibited. This is thought to be mainly due to the increasing shallowness, hence implying a larger vulnerability to the combined action of tidal and wave-induced currents. This also means that the dynamics of the area can hardly be proven by cross-bedding structures or laminations in general. Moreover, due to the homogeneous nature of the fine sandy sediments, hardly any textural differences can be detected visually. However, it has to be emphasised that most of the boxcores were taken in July 1994, thus representing fair-weather conditions.

The sedimentary sequences along the sandbanks

At some locations, along the gentle and steep slope of the banks, horizontal laminations can be observed. The sedimentary pattern is well sorted and sometimes fining upward sequences are present. The horizontal laminations are mainly attributed to wave action, whilst the fining upwards pattern is likely caused by a tidally-driven upslope transport along the gentle slope of the sandbanks. As mentioned in the previous paragraph, superimposed dune-like features are generally rather scarce, though it is not sure whether boxcores retrieved from such a morphology would witness any layering, due to the homogeneous nature of the sediments.

The sedimentary pattern along the Baland Bank does not show any bedding structures. As will be demonstrated in the following paragraph, the strength of the current induces active sorting processes whereby fines are actively being washed out. As those boxcores were taken in the period autumn - winter, it might be possible that laminations are preserved under very calm conditions. However it also seems likely, that these would be wiped out rapidly.

The sedimentary sequences along the swales

Due to the depth of the swales, the effect of wave action is generally limited, and thus the sedimentary pattern is likely to be bioturbated. This means that possible laminations are faded or wiped out by faunal activity. Depending on the shape and the dynamics of the swales, the sedimentary sequences can consist of an admixture of fine, medium or even coarse-grained sands together with shelly material (single and doublets). The matrix remains fine sandy and at the surface *Polychaetes* can be present. This is the case in the Westdiep swale (also its northern branch), where such an admixture of sediments can be found. Indeed, as shown in the previous chapter, the current velocity can be fairly high and under rougher conditions, a lot of sediment can be advected, as will be shown later on. It is believed that reinforced tidal currents are able to entrain shelly material along the swales, and that deposition occurs once the current decelerates. Under calmer conditions, bioturbation occurs, homogenising the sedimentary pattern. This is in contrast to the Grote Rede swale, where merely a complete homogenised sedimentary pattern is found, consisting of a fine sandy matrix and some *Polychaetes* at the top. Moreover, an important admixture of clay is present, which is likely deposited under slack water or calm conditions. However, the origin of a facies consisting of sand and mud can be different in origin (BASTIN 1976):

- the mud can be deposited on top of sandy sediments during slack water or calm conditions; the presence of such facies is highly dependent on the time of surveying and the meteorological conditions;
- a mixture of sand with some mud and clay can occur; sand and mud can be deposited simultaneously or the mud can diffuse through the underlying sandy deposits; or eroded clay pebbles that are transported with the current can diffuse into a sandy seafloor (diffusion into underlying sandy deposits or into overlying deposits in case they are already buried with sand), the latter process is observed west of Nieuwpoort;
- an alternation of sand and mud or clay layers can originate from the flood and ebb currents, each having a different sediment source.

The muddy deposits, observed near the foot of the steep slope of the Stroombank, may originate from spoil deposits of Nieuwpoort Harbour. By means of a long pipe, mud is dumped directly into the nearshore area. Referring to Section 2.2, a localised mud plume exists around the harbour of Nieuwpoort. During slack water and calm conditions, this fine-grained material may settle out in areas that are somewhat weaker in dynamics.

The massive occurrence of clay in the Kleine Rede remains peculiar. Unlike mud, clayey sediments have a high degree of compaction and their plasticity is much higher. The question remains if the compacted clay layers are recently compacted mud layers, or if they are have a relict origin (Tertiary or Quaternary mud). BASTIN (1974) had the impression that except for the Westdiep swale, the compaction is fairly recent. Still, without ^{14}C dating, this remains speculative. It has to be emphasised that the currents in the Kleine Rede are high and it seems likely that only the upper small veneer of sand is representative of the hydrodynamic active facies.

The sedimentary sequences along the shoreface

The shoreface sedimentary sequences could be compared with those of the sandbanks, although, up to a level of - 4 m, intercalated clay layers can still be found and the matrix remains reduced. Only the foreshore is characterised by a complete homogenised fine sandy matrix. Observations of the sea surface under a variety of conditions demonstrate that a lot of fine-grained material is present in the Kleine Rede swale. This kind of washload strongly aligns with the flooding tide and has merely a patchy appearance during slack water. Due to the relative abundance of this material, it may settle out under calm conditions. Wave action will definitely play its role in the shallower areas.

Relationship between flora, fauna and sediments

On the basis of the boxcores, some correlation between the presence of fauna and the depositional environment can be put forward. Evidence of fauna or faunal activity seems to be restricted to moderately active areas. Remarkable is the presence of *Lanice conchilega* in the northern branch of the Westdiep swale, the eastern prolongation of the Nieuwpoort Bank and in the Grote Rede swale. The depositional environment is characterised by a fine sandy matrix, which can be highly reduced. It is believed that suspension load controls their existence. Apparently, *Lanice conchilega* can withstand deposition of fine-grained material. It seems likely that the tubes of the tube-building polychaete worm favour the stability of the morphology. Fields of *Lanice conchilega* are also reported and observed along the northern slope of the Trapegeer, somewhat west of the study area (DEGRAER et al. (1999)).

Spisula subtruncata is also indicative of a specific depositional environment. From their distribution, it is clear that those filter feeders prefer areas characterised by a suspension load on a regular basis, a homogeneous fine sandy matrix, without a major admixture of silty to clayey sediments; this would block their filter system. The ideal environment seems to be the foot of the gentle slope of the sandbanks. The interaction of the current with the sandbanks gives rise to localised current accelerations.

Some of the boxcores clearly demonstrate feeding traces of *Echinocardium cordatum*. Those sea urchins were regularly observed along the gentle slope of the Nieuwpoort Bank indicating the lesser activity of this sandbank.

The relationship of fauna and sediments in the near coastal area is worked out in detail by (DEGRAER (1999)).

The homogenised nature of the upper 10 cm of some of the boxcores taken in July 1994, may also be caused by algae bloom, penetrating from the surface into the bed. Indeed, during all the sampling campaigns in the period 1995-1999, following quiet but especially warm conditions, an abundance of *Phaeocystis* could be observed in the surface waters. It seems plausible that a settling out of a large amount blurs the upper few cm of the seafloor, fading out existing traces.

BASTIN (1974) also mentioned the importance of biotic agents, such as a colony of molluscs (mainly *Cardium edule*) in the production of muddy sediments. He mentioned the dimensions of faecal pellets, approximating spheres of about 0.3 mm^3. Those are composed of silt-sized grains, glued by the mucus of organisms. The binding forces strengthen the particles, but make them also easier to deposit. Although his arguments were based on observations on a foreshore along the East Coast, it seems likely that these processes also occur in other places that witness high densities of organisms.

5.3.4. Surficial sediment characteristics

5.3.4.1. Characterisation of the surficial sediments in the near coastal area

From the intensive sampling campaigns, it is clear that the western part of the Belgian littoral zone is dominated by fine sandy surficial sediments, having a mean grain-size in the range of 125 to 250 µm (3 - 2 ϕ). In general, the sediments on the Coastal Banks have a pronounced unimodal distribution with a mean varying around 250 µm (2 ϕ). In most cases, 99% of the coastal bank samples consist of the sand fraction, though the surrounding swale samples have a mean in the range of very fine sands (62.5-125 µm / 4 - 3 ϕ) and are characterised by a higher silt-clay to sand ratio. The heterogeneous nature of the latter has been discussed in Section 5.3.1 and was also confirmed in Section 5.3.3. Medium surficial sands occur at the interaction zone with the more offshore Flemish Banks and closer to the coast, in areas with higher dynamics. Figure 5.19 is a representation of the grain-size characteristics in the near coastal area based on surficial sediment sampling in December 1995.

On the basis of the shape of the grain-size distribution curves and the derived grain-size parameters, a distinction can be made between the different environments. Analogous to DE MAEYER & WARTEL (1988) the grain-size frequency curves were grouped into 5 classes. Their observations were based on 100 surficial samples, taken along 7 transects across the Nieuwpoort Bank and Stroombank (1980-1983). As demonstrated in Figure 5.19, the subdivisions are also valid for the present investigation.

- Unimodal class: the frequency distribution curve is almost a straight line on a semi-logarithmic scale; the mode varies around 210 µm; the sediments are well sorted and only negligible admixtures occur at the extremities of the distribution. DE MAEYER & WARTEL (1988) mention their occurrence along the shoreface, the crest of the sandbanks and along the lower seaward flanks of the banks, although they are restricted to the dynamic areas.

- Unimodal-tailed: the main part of the frequency distribution of these sediments forms a straight line on a semi-logarithmic scale; however tailing off occurs at either the fine (subclass A) or at the coarse extremity (subclass B). Subclass A is found along the landward flank, whilst subclass B is mostly found along the lower seaward flank of the sandbanks. Both classes occur in the northern branch of the Westdiep swale.

- Heterogeneous class: represents moderately to poorly sorted sediments. Poor sorting is due to the occurrence of very fine sediments. Some coarser sediment may also occur, causing a concave bending of the coarser part of the frequency distribution. They may occur along the shoreface, the foot of the landward flank of the sandbanks and the swales.

- Very heterogeneous: very poorly sorted, the bulk of the sand is finer than 125 µm and 20-50 % of the distribution consists of particles smaller than 2 µm. These are representative of the swales, especially of the Grote Rede swale.

Figure 5.19 – The grain-size characteristics in the near coastal area based on surficial sediment sampling in December 1995.

The amount of calcium carbonate within the sediments was in general not determined, as those values are largely dependent on the sampling error. Mostly, the percentage of coarser material (> 500 μm) represents the shell fraction. However, those values have to be interpreted with care as one can hardly predict whether the grab penetrates in an area where shells are locally accumulated. BASTIN (1974) tried to find a relation between the amount of calcium carbonate as found offshore, and the percentages found along the beach based on a study of DEPUYDT (1972). However, no systematic relation could be established. Only more to the west, where there is a more direct contact of offshore and beach deposits, the mean calcium carbonate amount of both environments seemed to resemble; the same was found for the grain-sizes. Where muddy deposits characterise the nearshore, more calcium carbonate is found in the offshore marine sands. The wave energy breaking on the beaches, will dilute the shelly material that is subsequently carried offshore, where it mixes with the muddy deposits and thus increasing its calcium carbonate content. This means that in general the nearshore marine sands are richer in calcium carbonate than the adjacent beach deposits. On a large scale the mean calcium carbonate amount diminishes from the Pas-de-Calais towards the Dutch coast.

On the basis of the volume percentages representing the fraction larger than 710 μm, the presence of bioclastic sediments in the study area could be depicted. Those samples are mostly composed of a mixture of biogenically derived debris and quartz sand. Their distribution is confined to areas with higher sediment dynamics, such as the Westdiep swale and the Baland Bank. Side-scan sonar observations in the Westdiep swale showed well-delineated patches having a different acoustic signature (Appendix B, West). It is thought that these correspond with an abundancy of molluscs. Moreover, these patches also occurred in the troughs of the dunes. On side-scan sonar registrations, those troughs showed up as regularly spaced, highly reflective, even toned signatures, whilst the finer grained gentle slopes of the dunes showed a weakly reflective signal. However, this contrasts with the side-scan imagery in the Baland Bank dune area (Appendix B). Here, the gentle slope of the dunes was highly reflective, whilst the troughs only had a small reflectivity. This is merely a reflection of the shallowness of the dunes than of differences in grain-size.

In the framework of this study, a large amount of samples has been taken to unravel the spatial and temporal variability of the coastal system. In this paragraph, the sediment distribution curves of some samples was discussed in order to differentiate between subenvironments. In the following paragraph, a more detailed analysis of the spatial variability of the grain-size fractions will be attempted. However, as a study of the morpho- and sedimentdynamics is envisaged, the final discussion will be focused on the areas with higher dynamics. The sediment dynamical implications of the observed differentiation of the surficial sediments will be discussed in paragraph 5.3.4.4.

5.3.4.2. Fraction analysis across morphological entities

Samples have been chosen according to their morphological position, and the volume percentages of each fourth of phi fraction of the sediments were plotted. Such a fraction analysis is an interesting tool, as it provides insight into the processes governing the coastal system. A depletion of fractions may be attributed to a transport of sediments, either by currents or by waves. The latter can be translated as wave winnowing. This will be discussed in more detail in Section 5.3.4.4.

Fraction analysis along a transversal profile comprising the Nieuwpoort Bank - Westdiep swale - Middelkerke Bank (Fig. 5.20)

The coarsest fractions (0.75 – 1 .00 ϕ / 590 – 500 μm) are present downslope the southern part of the Middelkerke Bank. Finer grains, but also fractions of 1.25 – 1.50 ϕ (420 – 350 μm) seem to be enriched at the base of the sandbanks. From the size 1.75 ϕ (300 μm) onwards, an upslope fining trend is observed, accompanied by a severe winnowing of the finer fractions at the base of the gentle slope. This is especially true for the range 2.00 – 2.50 ϕ (250 – 180 μm). The upslope enrichment seems also to be valid along the southern part of the Middelkerke Bank. However, grain-sizes finer than 2.50 ϕ (180 μm) are washed out here. Along the Nieuwpoort Bank, this is also the case for grains having a size less than 2.75 ϕ (150 μm).

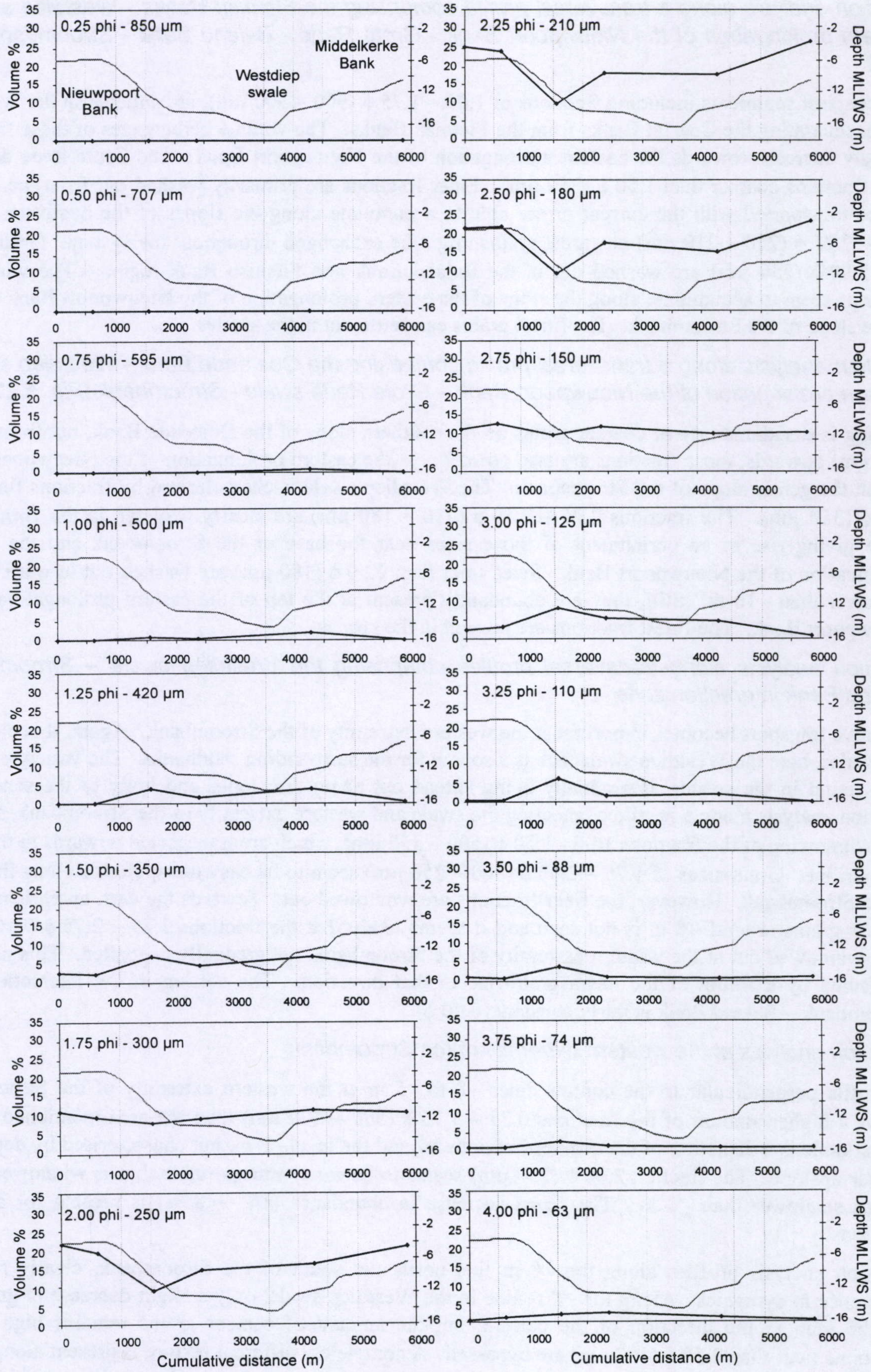


Figure 5.20 - Fraction analysis along a transversal profile comprising the Nieuwpoort Bank - Westdiep swale - Middelkerke Bank (grain-size data of December 1995) (samples 3 – 8 in Figure 5.19).

Fraction analysis along a transversal profile comprising the Flemish Banks - Westdiep swale – eastern prolongation of the Nieuwpoort Bank - Grote Rede - Baland Bank - Stroombank (Fig. 5.21)

The coarsest sediments including fractions of 1.00 – 1.75 ϕ (500 – 300 µm), are situated in the Westdiep swale, separating the Coastal Banks from the Flemish Banks. The volume percentages of these fractions strongly decrease towards the eastern prolongation of the Nieuwpoort Bank. The Grote Rede does not have fractions coarser than 1.50 ϕ (350 µm). Finer fractions are primarily washed out from the swales, can be transported with the current or are able to accumulate along the slopes of the bedforms. From 2.00 – 2.25 ϕ (250 – 210 µm) onwards, grains might be exchanged throughout the system. Grains finer than 2.00 ϕ (250 µm) are washed out in the Baland Bank and Flemish Bank region. The winnowed fractions seem to accumulate along the slope of the eastern prolongation of the Nieuwpoort Bank and the gentle slope of the Stroombank. The finest grains can settle out in the swales.

Fraction analysis along a transversal profile comprising the Oostende Bank - Westdiep swale – eastern prolongation of the Nieuwpoort Bank – Grote Rede swale - Stroombank (Fig. 5.22)

Striking is the abundance of coarser grains on the southern slope of the Oostende Bank, but from 1.25 ϕ (420 µm) onwards, those fractions are also present near the eastern prolongation of the Nieuwpoort Bank and on the gentle slope of the Stroombank. The Westdiep swale is characterised by fractions finer than 1.50 ϕ (350 µm). The fractions 2.25 – 2.50 ϕ (210 – 180 µm) are clearly depleted in the Grote Rede swale giving rise to an enrichment of those sizes near the base of the Stroombank and the eastern prolongation of the Nieuwpoort Bank. Sizes finer than 2.50 ϕ (180 µm) are washed out in water depths shallower than - 10 m. Still, they are abundantly present at the top of the eastern prolongation of the Nieuwpoort Bank. The finest fractions are present in the swales.

Fraction analysis along transversal profiles comprising the Westdiep swale – Stroombank / Baland Bank interaction zone

Selective transport becomes important at the western extremity of the Stroombank. Again, it is clear that the swales, here the Westdiep swale, act as a source for the surrounding sandbanks. The variety of grain-sizes found in the swales, is gradually being spread out along the slopes and body of the sandbanks. Fraction analysis along a profile connecting the swale and western extremity of the Stroombank, shows a first winnowing of the fractions 1.00 - 1.50 ϕ (500 – 350 µm), which are transported upwards to the - 8 m contour line. Grain-sizes of 1.75 – 2.00 ϕ (300 – 250 µm) seem to be easy transportable along the slope of the Stroombank. However, the finer fractions are winnowed out. Towards the east, an enrichment of coarser grains around - 8 m is not seen and it seems likely that the fractions 2.25 – 2.75 ϕ (210 – 150 µm), winnowed out at the western extremity of the Stroombank, are gradually deposited. This might be confirmed by a fining of the mean grain-size in that direction. The sorting in the interaction zone Stroombank – Baland Bank is fairly constant (0.40 ϕ).

Fraction analysis at the western extremity of the Stroombank

A profile perpendicular to the contour lines - 8 to - 5 m at the western extremity of the Stroombank, shows a higher amount of the fractions 0.75 – 1.75 ϕ (590 – 300 µm) than the area mentioned before. Remarkable is a depletion of the coarser fractions around the level - 8 m, but characterised by deposition further upslope. The fraction 2.00 ϕ (250 µm) seems to be easily transportable, but is winnowed out at depths shallower than - 5 m. The sharp decrease in abundance (16 $\rightarrow$ 8 %) is present for all finer fractions.

Fraction analysis profiles along the - 8 m line north and south of the Stroombank, clearly reflect a difference in dynamics. Along the - 8 m line in the Westdiep swale, only a slight decrease in grain-size can be seen in the direction of the current, but the amount of coarser grains remains high (7 %). Fractions finer than 2.50 ϕ (180 µm) are bypassed. A completely different texture is present along the - 8 m line, south of the Stroombank. Coarser fractions are generally absent, except near the steep side of the sandbank. The samples contain fractions finer than 4.00 ϕ (63 µm).

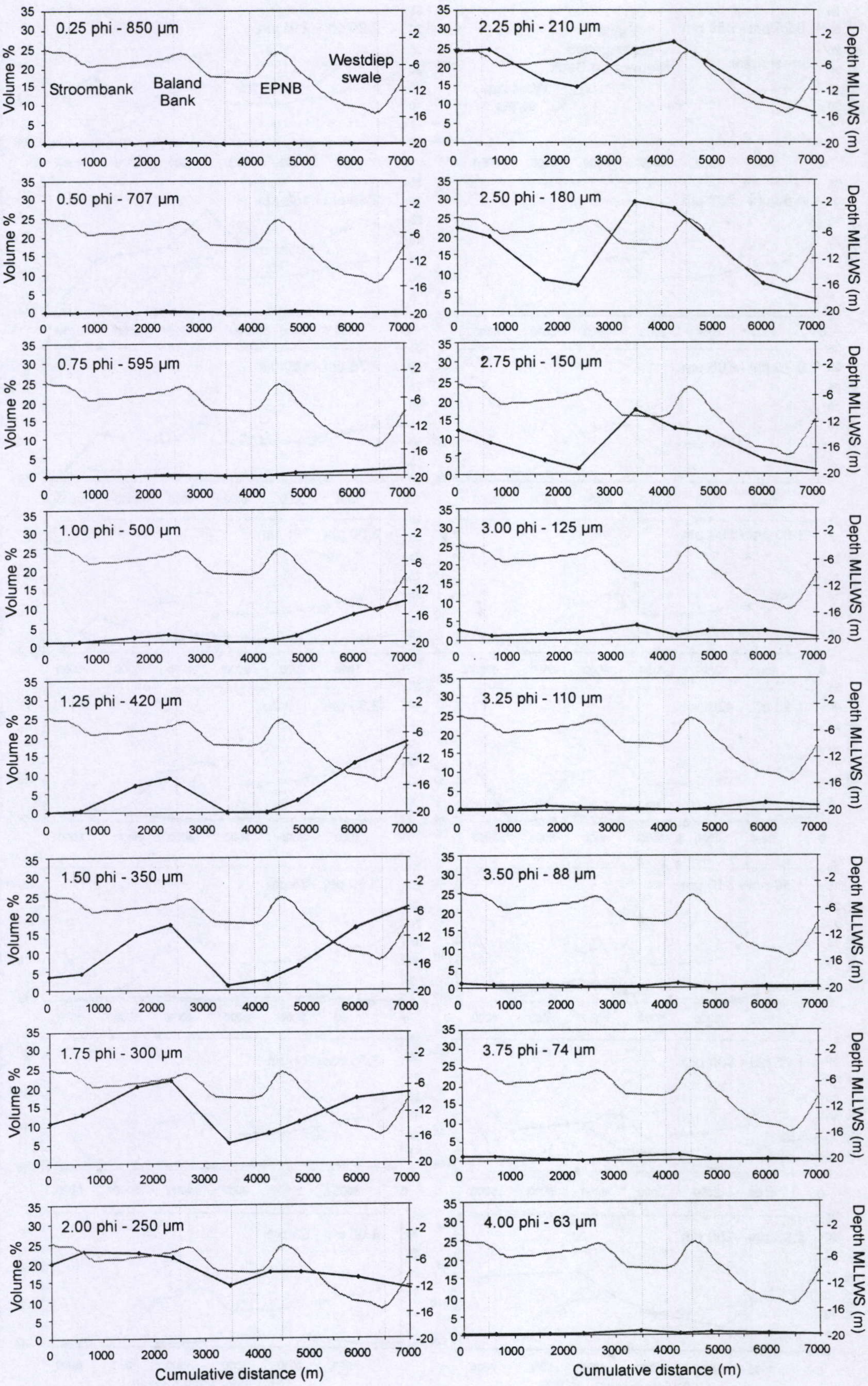


Figure 5.21 - Fraction analysis along a transversal profile comprising the Flemish Banks - Westdiep swale – eastern prolongation of the Nieuwpoort Bank - Grote Rede - Baland Bank - Stroombank (grain-size data of December 1995) (samples 16 – 24 in Figure 5.19).

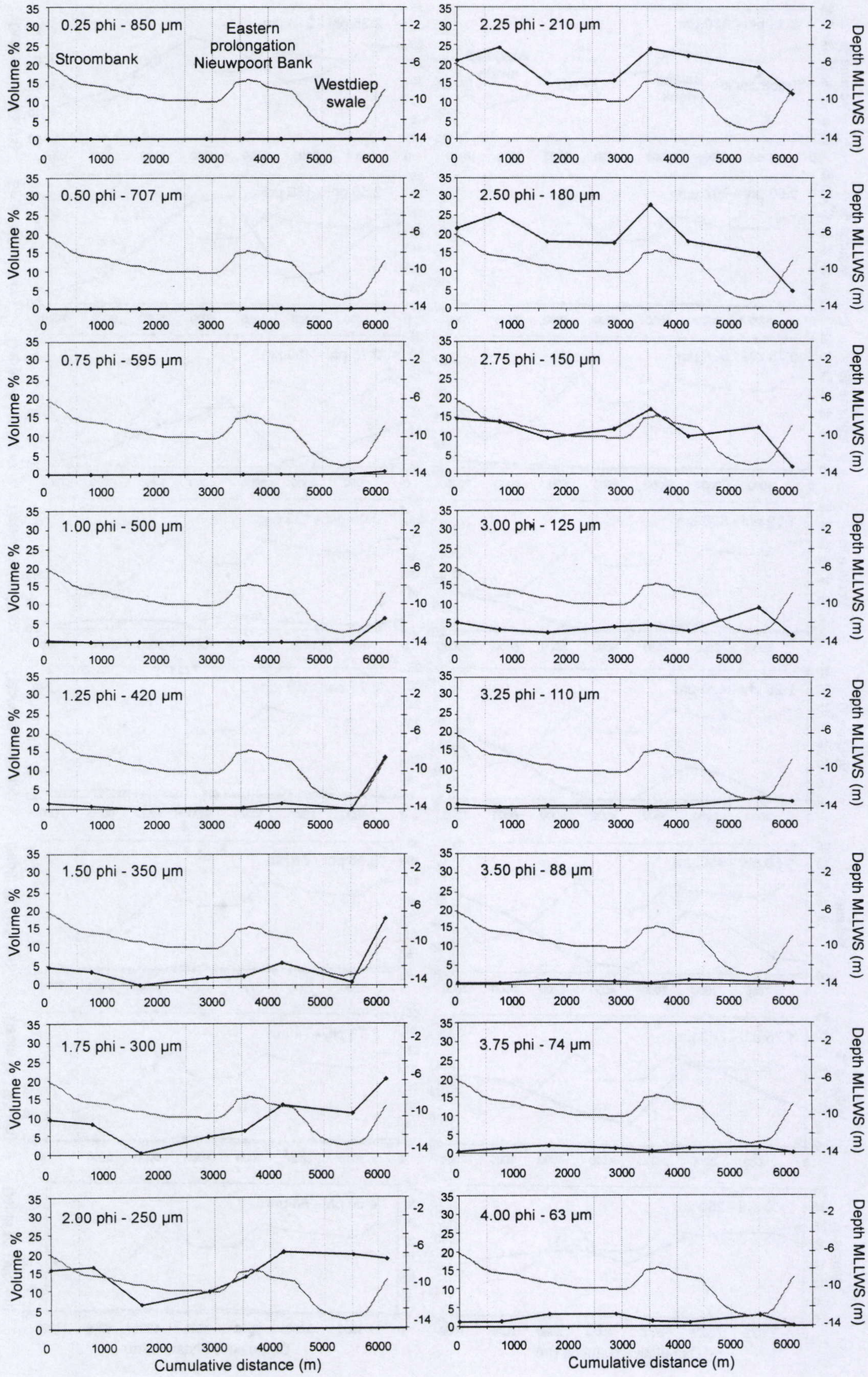


Figure 5.22 - Fraction analysis along a transversal profile comprising the Oostende Bank - Westdiep swale – eastern prolongation of the Nieuwpoort Bank – Grote Rede swale - Stroombank (grain-size data of December 1995) (samples 29 –36 in Figure 5.19).

Fraction analysis along longitudinal profiles in the Westdiep swale

Along the axis of the swale a variety of grain-sizes is present. Deeper than - 10 m, a significant amount of fractions finer than 3.00 ϕ (125 μm) (up to 5 %) testifies of the lower dynamics; coarser fractions are also less abundant than higher up. Along the slope towards the Baland Bank, in depth ranging from - 10 m to - 8 m, no real differentiation can be seen; however, fractions from 1.25 to 2.25 ϕ (420 – 210 μm) are predominantly present. The finer fractions are washed out.

Following fractions along the - 8 m line towards the Baland Bank, confirms the higher dynamics along a stretch of approximately 1600 m from the western extremity of the Stroombank. More to the east, coarser grains in the range of 1.00 – 1.75 ϕ (500 – 300 μm) decrease in abundance. From 2.00 ϕ (250 μm) on, a gradual enrichment is seen towards the Baland Bank.

A longitudinal profile shallower than - 8 m, away from the western extremity of the Stroombank and slightly oblique to the - 7 and - 6 m contour lines, shows that the coarsest fractions are absent or very low in amount. From 1.50 ϕ (350 μm) onwards, some gradation can be remarked. The fractions 2.00 - 2.25 ϕ (250 – 210 μm) are abundantly present. From the fraction 2.50 ϕ (180 μm) onwards, winnowing is observed shallower than - 6 m.

The fraction analysis learns that the sediments are mainly subjected to 3 processes: an enrichment of sediments from the swales to the foot of the sandbanks, an upslope fining upward transport and finally a winnowing or washing out of the finest fractions. Table 5.07 gives a synthesis of these processes for each morphological unit. For each process, a range of fractions is presented. This may reflect a difference in dynamics along the sandbanks or may also be due to the variation in season during which the samples were taken.

Table 5.07– Synthesis of the fraction analysis.

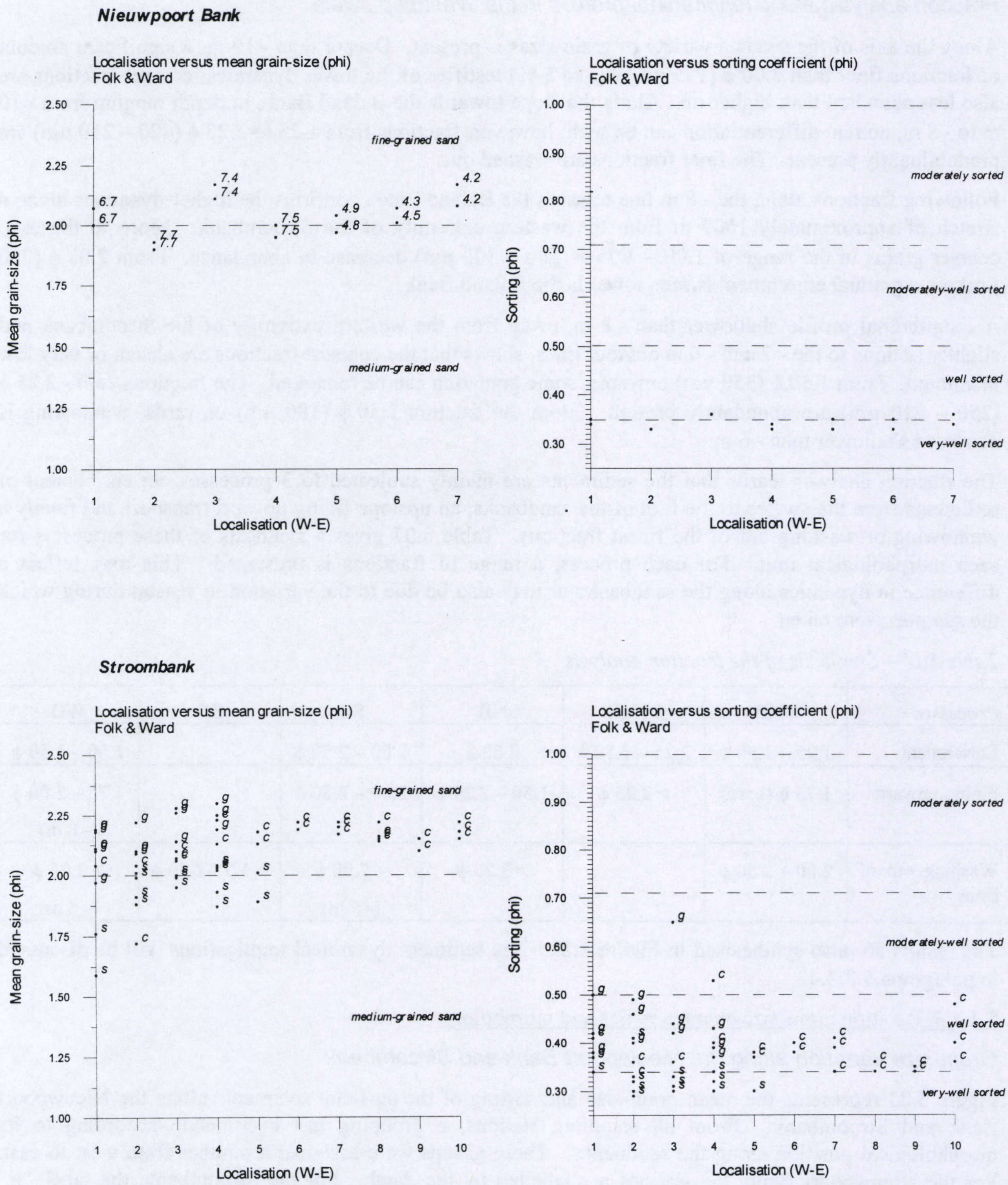
Processes	SMB	EPNB	NB	SB	BB	WD
Enrichment	1.25 – 1.50 ϕ	2.25 – 2.50 ϕ	2.00 ϕ	2.00 – 2.50 ϕ		1.00 – 1.50 ϕ
Fining upward	1.75 ϕ (base)	> 2.25 ϕ	1.50 – 2.25 ϕ	2.00 – 2.50 ϕ		1.75 – 2.00 ϕ (- 8 m)
Washing out of fines	2.00 – 2.50 ϕ		> 2.25 ϕ	> 2.00 ϕ (- 5 m)	> 1.75-2.00 ϕ	> 2.25 ϕ (- 6 m)

The results are also synthesised in Figure 5.29. The sediment dynamical implications will be discussed in paragraph 5.3.4.4.

5.3.4.3. Relation grain-size characteristics and morphology

Grain-size variation along the Nieuwpoort Bank and Stroombank

Figure 5.23 represents the mean grain-size and sorting of the surficial sediments along the Nieuwpoort Bank and Stroombank. From all sampling stations, a grouping has been made according to its morphological position along the sandbanks. These groups were assigned a number from west to east. For the Nieuwpoort Bank, the stations are labelled by the depth. For the Stroombank, the label *"g"* represents a sample taken along the gentle slope, *"c"* along the crest and *"s"* along the steep slope. Only the data points are chosen, that were at least sampled twice. The effect of the period and time of sampling will be discussed in the following chapter.



Note: In localisation point 5, the mean grain-size along the gentle slope reached values of 3.12 up to 3.51 phi

Note: In localisation point 5, the sorting along the gentle slope reached values of 2.08 up to 2.66 phi

Figure 5.23 – The longitudinal variation in grain-size and sorting of the surficial sediments of the Nieuwpoort Bank and Stroombank.

In general, the bulk of the surficial sediments of the Nieuwpoort Bank and Stroombank represent fine-grained sands. Only the western end of the sandbanks is characterised by medium sands and partly also the steep slope. The Stroombank appears to have a somewhat coarser texture than the Nieuwpoort Bank. The majority of the sediments are well to very well sorted. The latter is apparent for the steeper slope. The sorting calculated according to FOLK & WARD (1957), shows only minor differences between both sandbanks. Using the moment measures, the surficial sediments of the Stroombank seem to be less differentiated than those of the Nieuwpoort Bank. The characteristics along the gentle slope are most variable.

Restricted to the same morphological position, the surficial sediments show a fining of the grain-size in a northeastern direction. No significant trend in the sorting can be perceived.

Figure 5.23 also demonstrates that the longitudinal variation in grain-size is inferior to the transversal differentiation. A clear gradient exists in the grain-size from the gentle slope up to the steeper slope. The sediments along the latter are coarser and generally better sorted. A profile covering both the Nieuwpoort Bank and the Stroombank has been sampled repetitively in the period 1995 – 1998, in order to validate the significance of the relation grain-size – morphology and to determine the temporal aspect. The latter will be discussed in the following chapter. A description of the boxcores taken along this profile is described in Section 5.3.3.1. Figure 5.24 is a representation of the cross-bank differentiation in the grain-size characteristics. The interpretation will be clarified in Section 5.3.4.4.

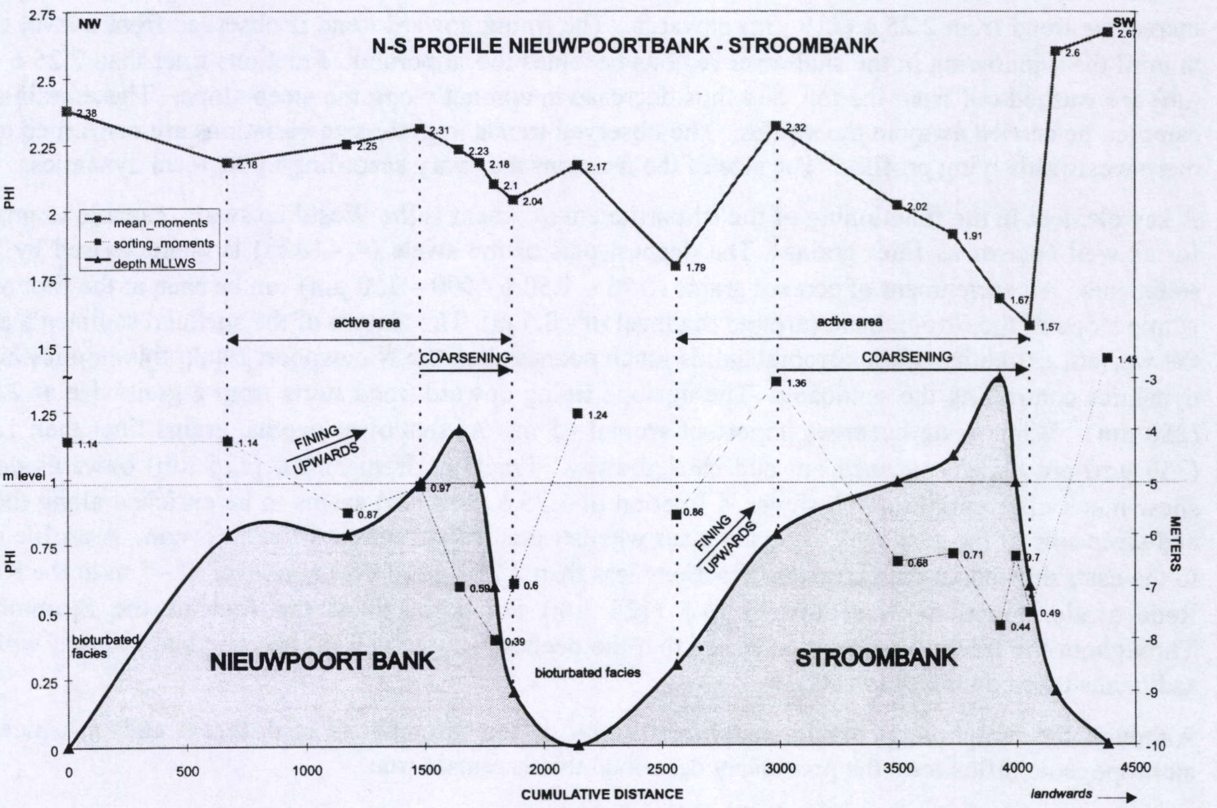


Figure 5.24 – A cross-bank transect over the Nieuwpoort Bank and the Stroombank showing differentiation in grain-size and sorting.

For both the Nieuwpoort Bank and the Stroombank, the grain-size distribution of the surficial sediments becomes generally coarser and better sorted in a cross-bank direction, although a fining-upward trend (# of 0.50 ϕ) in grain-size is seen from the swales towards the gentle slope of the bank. From a level of - 5 m for the Nieuwpoort Bank and from - 6 m for the Stroombank, the mean grain-size becomes progressively coarser (# of 0.75 ϕ). Along the Nieuwpoort Bank, the sorting shows the same trend; however, more bias is observed along the Stroombank. For both sandbanks, the coarsest sediments are deposited along the steeper, landward slope. Generally, the surficial sediments in the troughs are finer, though as outlined before, it was suspected that the relatively coarser texture of the Westdiep swale in the interaction zone between both sandbanks is rather anomalous. Still, a break in the grain-size characteristics can be seen. In the Kleine Rede, the change in the mean value of the grain-size is much higher (# of 1.10 ϕ). Generally, the swales are bioturbated. The cross-bank fining-upward trend, followed by a coarsening and a deposition of the coarsest sediment along the steep slope, was found to be valid for all sampling campaigns, as well temporally as along other profiles on both the Nieuwpoort Bank and the Stroombank.

A fraction analysis along this profile (Fig. 5.25) demonstrated that on the Nieuwpoort Bank the action of hydrodynamic forces upon the seafloor is reflected from a grain-size of 1.25 ϕ (420 μm) onwards. Fractions in the range of 1.50 – 2.25 ϕ (350 – 210 μm) are progressively winnowed along the gentle slope, which is reflected by an upslope decreasing trend in abundance. The eroded sediments are gradually deposited along the steep slope with the coarsest sediments being present around - 7 m (15 – 30 % difference in abundance). The upslope decreasing trend in abundance changes to an upslope increasing trend from 2.25 ϕ (210 μm) onwards. The fining upward trend is observed from a level of - 6 m until the winnowing in the shallower regions becomes too important. Fractions finer than 2.25 ϕ (210 μm) are washed out from the top, and thus decrease in amount along the steep slope. These grain-sizes can then be carried away in the swales. The observed trends in grain-size variations are confirmed along more westwards lying profiles. The size of the fractions may vary according to the local dynamics.

A key element in the functioning of the tri-partite environment is the Westdiep swale, capable to provide for as well coarser as finer grains. The deepest part of the swale (< - 10 m) is characterised by finer sediments. An enrichment of coarser grains (0.75 – 1.50 ϕ / 590 – 350 μm) can be seen at the foot of the gentle slope of the Stroombank (around the level of - 8.5 m). The texture of the surficial sediments along the western extremity of the Stroombank is much coarser than the Nieuwpoort Bank; this implies higher dynamics controlling the sandbank. The upslope fining upward trend starts from a grain-size of 2.00 ϕ (250 μm). Winnowing becomes important around - 5 m. At shallower depths, grains finer than 1.50 ϕ (350 μm) are already washed out and carried away. Fractions from 3.00 ϕ (125 μm) onwards do not show much differentiation. However, a fraction of 3.25 ϕ (110 μm) seems to be enriched along the top and steep side of the sandbank. It is not clear whether this fraction has a different origin. A profile more to the east, showed an enrichment of fractions less than 2.25 ϕ (210 μm) at a level of - 7 m in the Kleine Rede swale. Fractions finer than 3.00 ϕ (125 μm) are enriched at the foot of the Stroombank. Throughout the fraction analysis, it seems that the deepest sample (- 9 m) has no clear relation with the sediments taken on the sandbank.

Although the morphology of the eastern extremity of the Stroombank is different and influenced by anthropogenic influences, the previously described trends remain true.

Grain-size variation across the Baland Bank dune area

In the Baland Bank dune area, the surficial sediments have mainly been sampled on two occasions. In November 1996, 4 boxcores and 20 surficial samples have been taken; in May 1997 the grid was extended to 40 sampling stations.

The area mainly consists of medium-grained sands that are moderately well sorted. This is in contrast to the better sorting of the sediments of the Nieuwpoort Bank and the Stroombank. The delineation with the fine to very fine sands of the swales is very sharp, as is the presence of the very large dunes.

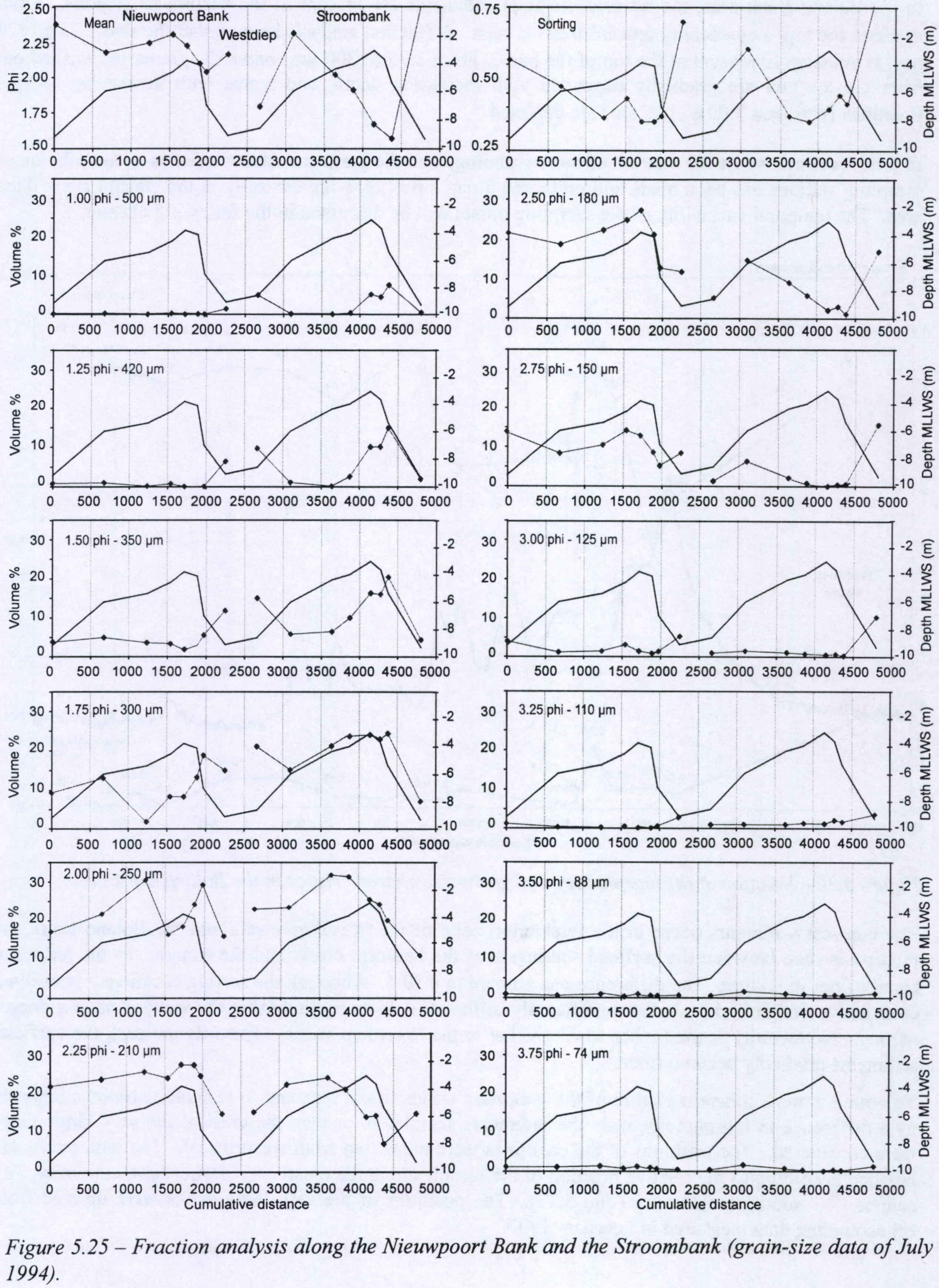


Figure 5.25 – Fraction analysis along the Nieuwpoort Bank and the Stroombank (grain-size data of July 1994).

In the Baland Bank area, the coarsest surficial sediments are present in the shallowest regions. From swale to the top, a coarsening upward trend is seen. A fraction analysis learned that the size 1.25 ϕ (420 μm) is abundantly present at the top of the bank. From 1.75 ϕ (300 μm) onwards, grains are washed out from the top and are gradually deposited with increasing depth, and hence with decreasing energy. Fractions finer than 3.00 ϕ (125 μm) are depleted.

In order to demonstrate the relation of the morphology and the grain-size characteristics, a compilation of sampling stations has been made and presented along a profile, lying centrally in the Baland Bank dune area. The temporal variability of the sampling points will be discussed in the following chapter.

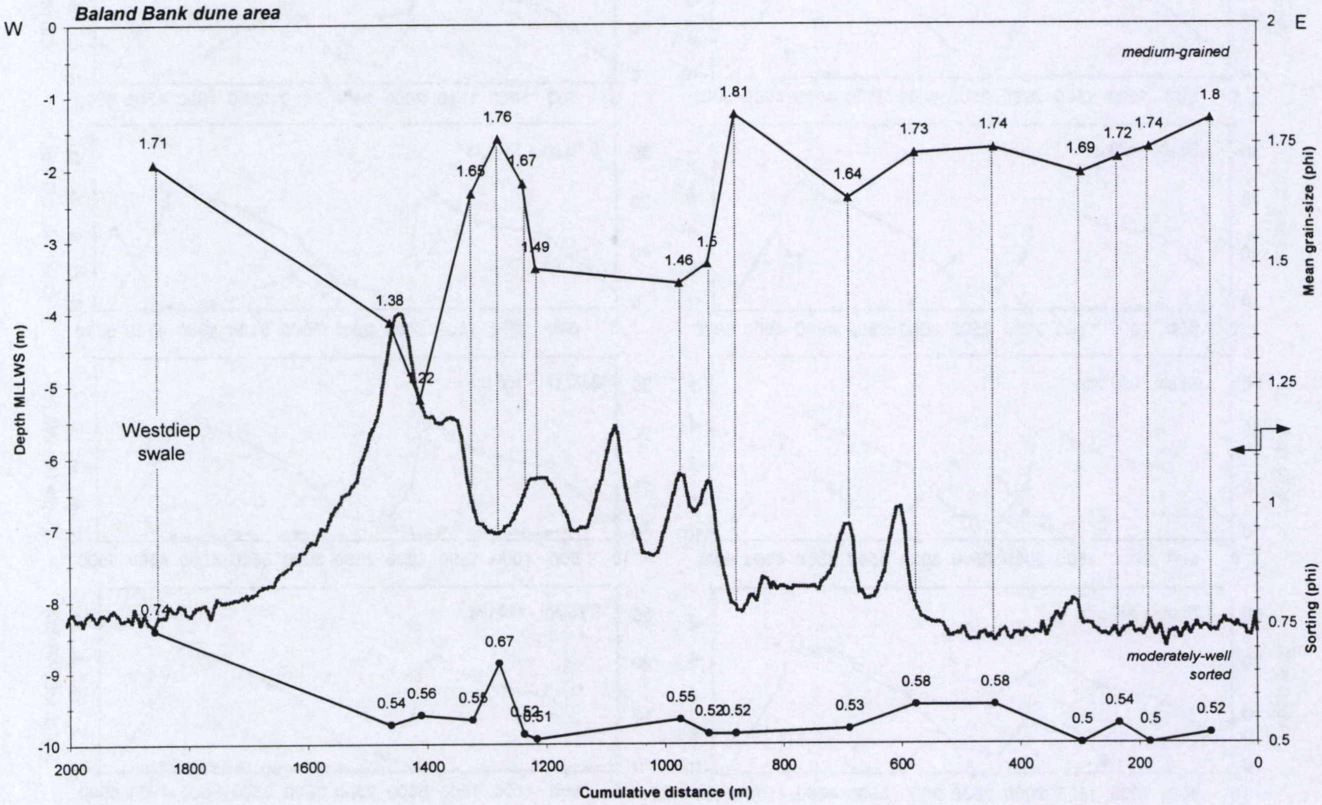


Figure 5.26 – Relation of the morphology and grain-size characteristics in the Baland Bank area.

The coarsest sediments occur in the interaction zone of the Westdiep swale and the Baland Bank. A relation is seen between the surficial sediments of the bedform crests and the troughs, as the latter are clearly finer in texture. The difference can amount to 0.30 ϕ. Although the sorting coefficient between a crest and a trough is not always significantly different, it is more likely that the troughs have a poorer sorting. Noteworthy is the higher sorting value in the Westdiep swale. Towards the east, the surficial sediments gradually become finer.

To obtain a more coherent picture of the grain-size trends in the area and to exclude variations imposed by a difference in morphology, only the sediments sampled at or near the crest of the very large dunes were considered. The positions of the crestlines were numbered from west to east. The data points are labelled according to the relative position of the sample along the crestline: *"n"* northern extremity, *"c"* central, *"s"* southern extremity (Fig. 5.27). The positions of the very large dunes were derived from echosounding data measured in February 1997.

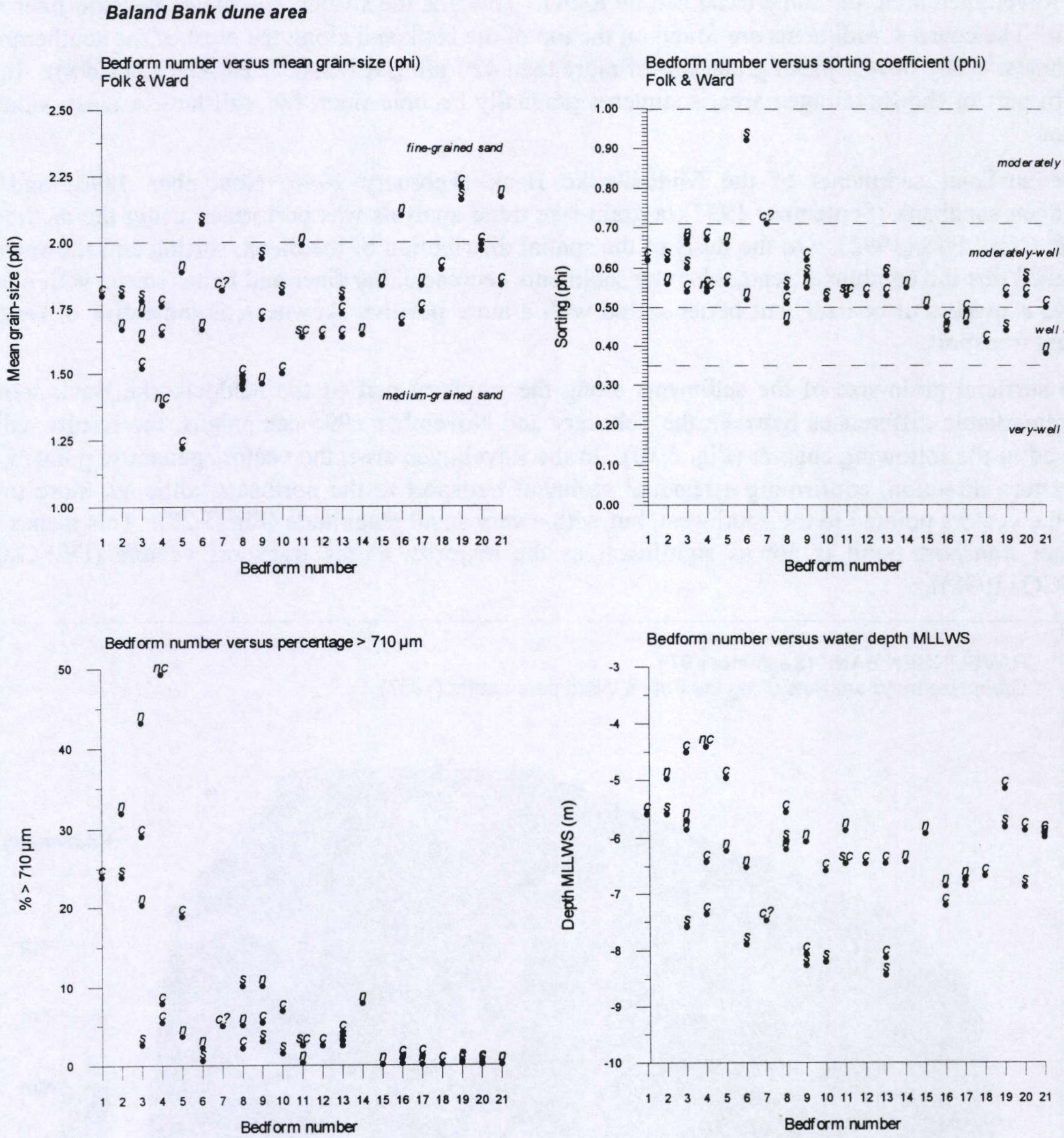


Figure 5.27 – Grain-size characteristics of the very large dunes in the Baland Bank area.

Figure 5.27 demonstrates the variation of some parameters for each very large dune. Apart from the lateral variation along a crestline, it is clear that the mean grain-size becomes finer towards the east. As the sorting also improves, this means that the sediment is mainly transported easterly. The highest percentage of the coarsest fraction (> 710 µm) occurs at the bank level and gradually reduces to zero. Figure 5.27 also demonstrates that the grain-size variation is not purely a function of water depth. The grain-size variation over large dunes has also been discussed by TERWINDT (1971), HOUBOLT (1968), SMITH (1969), McCAVE & LANGHORNE (1982), HARRIS et al. (1990), HOUTHUYS (1990) (Oostdijk Bank).

Grain-size variation in the offshore areas Ravelingen and in the southern part of the Middelkerke Bank

The southern part of the Middelkerke Bank is dominated by fine to medium sands with a mean grain-size of 275 µm. With increasing depth, the sediments become gradually finer. The sediments are well sorted and the distributions are predominantly skewed towards finer diameters (O'SULLIVAN 1997).

In the Ravelingen area, the same trend can be found. Towards the swales, sediments become finer than 250 µm. The coarsest sediments are found on the top of the bank and along the crest of the southernmost large dunes. They have a mean grain-size of more than 420 µm (DELGADO BLANCO (1998)). In the northern part of the Ravelingen area, sediments gradually become finer, but still have a mean value of 300 µm.

On the surficial sediments of the Middelkerke Bank (February 1996, November 1996) and the Ravelingen sandbank (September 1997), a grain-size trend analysis was performed using the method of GAO & COLLINS (1992). On the basis of the spatial distribution of the mean, sorting and skewness, it is believed that the combined trend, whereby sediments become either finer and better sorted with a more negative skewness or coarser, but better sorted with a more positive skewness, is indicative of residual sediment transport.

As the surficial grain-size of the sediments along the southern part of the Middelkerke Bank showed some remarkable differences between the February and November 1996 campaigns, the results will be discussed in the following chapter (Fig. 6.10). In the Ravelingen area, the vectors generally pointed in a northeastern direction, confirming a residual sediment transport to the northeast, although more to the north, the vectors pointed to the southwest, but with a very small magnitude (Fig. 5.28). This means that the latter transport trend is not as significant as the majority of the transport vectors (DELGADO BLANCO (1998)).

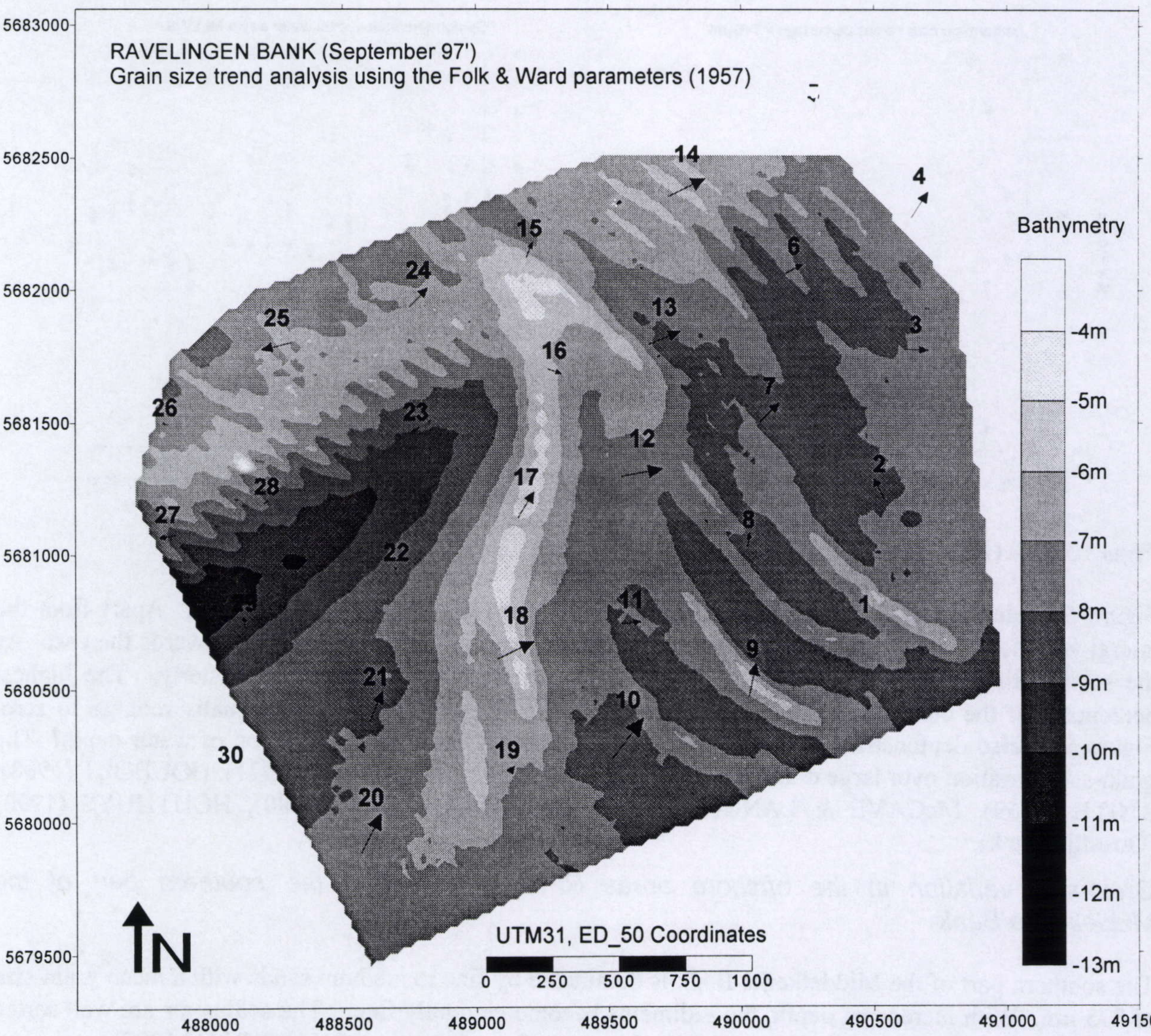


Figure 5.28 – Ravelingen. Grain-size trend analysis superimposed on a digital elevation model of the area (September 1997).

5.3.4.4. Sediment-dynamical implications

From the differentiation of the frequency distribution curves, representative of the near coastal area, some deduction can be made for the sediment transport processes. According to DE MAEYER & WARTEL (1988) based on MIDDLETON (1976), the unimodal class of sediments corresponds to a transport of sediment mainly as intermittent suspended load. The fine-tailed unimodal class is a reflection of sediment transport as suspended load, whilst the coarse-tailed unimodal class represents traction load. The moderately to poorly sorted sediments of the heterogeneous class are mainly deposited from an intermittent suspended load though the admixture of very fine particles indicates that deposition from a suspended load also occurred simultaneously with, or successively to, deposition from intermittent suspension. The grain-size distribution of sediments from this class indicates that major fluctuations in transport velocity occurred at the site of deposition. The very heterogeneous sediments are restricted to the swales, representing deposits of a suspended load.

From the fraction analysis, it can be stated that grains finer than 2.00 – 2.25 ϕ (250 – 210 µm) are easily exchanged throughout the system. Active sediment transport seems however to be restricted to the shallower areas. The fraction analysis demonstrated that sediments deeper than - 8 to - 9 m do not dynamically interact; hence they belong to another sedimentary environment. This confirms the findings of the sediment transport calculations, presented in the previous chapter. It seems that the sediments in the near coastal area are mainly subjected to 3 processes.

Firstly, an enrichment of sediments, or coarser grains in particular, is observed at the foot of the sandbanks around a level of - 8 m. This enrichment is most likely at the base of the gentle slope of the sandbanks, and is enhanced by Coriolis forces, inducing in the Northern Hemisphere a veering of the current to the right of its direction. This process seems to be valid throughout the area, meaning that the sediments of the swales act as a source for the sandbanks. The coarsest fractions are indeed found in the swales. This is especially the case for the Westdiep swale: its northern branch witnesses fractions of 1.00 – 1.75 ϕ (500 – 300 µm). These are hardly found in the surficial sediments of the sandbanks, indicating that these fractions are not actively exchanged throughout the coastal system. This potential of sediment movement in the swales seems to correspond with the findings of the sediment transport modelling. However, the question remains how active these processes need to be considered. *Is the enrichment a fairly continuous process of traction load or is the result of enhanced tidal current and wave action, and thus related to storm conditions ?* It needs emphasis that although the surficial sediments of the swales are composed of a mixture of grain-sizes, they have a mean grain-size that classifies them as being very fine sands having a high silt-clay to sand ratio. Although the swales can be regarded a conductor of coarser grains, they are the most likely environment for the deposition of the finest fractions due to their depth. Moreover, they are mostly characterised by a bioturbated facies. This pleads for an episodic nature of the enrichment process.

Secondly, the sediments enriched at the base of the sandbanks are subdued to a fining upward trend. Indeed, it seems that fractions are gradually being winnowed, transported upslope and deposited along the pathway. The fractions involved are dependent on the dynamics of the area and range from 1.75 ϕ to 2.50 ϕ (300 – 180 µm). It is believed that this trend is tidally driven, and reflects the progressive acceleration of the current over the sandbanks (Bernoulli effect). The current-driven fining upward trend can be traced up to a level of - 6 to - 5 m.

Thirdly, shallower than - 5 m, wave action becomes important and the finer fractions are actively being washed out. Due to this wave winnowing, the coarsest sediments occur along the upper steep slope. The winnowed finer fractions can be deposited downslope or be carried away with the current. This trend is observed under a variety of conditions, from mild to rougher weather and as well during neap as spring tide. However, this process will be most active during the ebbing tide when the water level is lowest. Breaking of the waves over the crest of the sandbanks is regularly observed (pers. observations). The wave base corresponding to waves of 0.5 m in height and a period of 3 s is about 7 m; hence shallower than this depth, sediments are affected by wave action. For the Stroombank, fractions less than 2.00-2.25 ϕ (250 – 210 µm) are being washed out. Possibly, these fractions are dynamically exchanged with the adjacent beaches.

The enrichment and fining upward trend seem to be valid along both sides of the sandbanks. Apart from the general distribution patterns, this was also exemplified by the volume percentages of the fractions 1.50 – 2.00 ϕ (350 – 250 μm) from the eastern prolongation of the Nieuwpoort Bank to the Grote Rede. On the one hand, wave action could winnow out grains on the eastern prolongation of the Nieuwpoort Bank, which are then progressively deposited towards the Grote Rede. On the other hand, it seems unlikely that the wave base under average conditions reaches as deep as - 8 m, meaning that it is more reasonable that currents are also responsible for an upslope fining trend from the Grote Rede to the eastern prolongation of the Nieuwpoort Bank. The same holds true in the Westdiep swale, meaning that the eastern prolongation of the Nieuwpoort Bank is maintained by a convergent sediment transport. This also explains the maintenance of the sandbanks.

The supposed higher dynamics in the Baland Bank area was confirmed during the fraction analysis. Transversal to the bank's axis, even fractions of 1.75 ϕ (300 μm) are progressively being washed out. This reflects the intense tide-topography interaction. The presence of medium-grained sands reflects the higher dynamics of the area. The grain-size seems to be proportional to the shear stress exerted on the sediments. The fines are actively being washed out and are deposited further downstream. The differentiation is thus a reflection of a diminishing shear stress from west to east. This process is fully controlled by the flood dominant current. Due to the high current velocities, it is believed that suspended load is entrapped in the eddy-like structure of the flow, imposed by the bedform geometry. The latter can also explain the occurrence of patches of bioclasts in the troughs of the bedforms. It is believed that shelly material is caught by turbulent eddies under high current velocities. Moreover, they may be easily transported by the current, owing to the platy nature of the shelly material. The grains eventually avalanche down the dune lee slopes and accumulate in the dune troughs. The abundance of platy bioclastic sediment in the troughs may cause a jamming effect between the grains, reduces the mobility of the bioclastic trough sediment and might get buried by migrating dunes. If they are not reworked during rougher time periods, they can give rise to a major bounding surface in the large 2-D dunes.

Out of the fraction analysis, the Stroombank and Baland Bank emerge as a separate sedimentary system. Given the abundance of grains in the range of 1.00 – 1.75 ϕ (500 – 300 μm) in contrast to the much lower volume percentages in the surrounding swales, it seems unlikely that the latter can act as a conductor of coarser grains. A winnowing of coarser grains along the slope reflects the higher dynamics of the western extremity of the Stroombank. This is likely due to an enhanced acceleration of the current.

5.3.5. Sedimentological map and inferred transport pathways – synthesis and discussion

The results presented in the previous paragraphs have been compiled in Figure 5.29. The shading from light to dark corresponds with surficial sediments having a mean grain-size within the range of respectively very fine (62.5-125 μm), fine (125-250 μm) and medium (250-500 μm) sand. The arrows indicate the sediment transport pathways inferred from grain-size characteristics. The triangles at the base of the arrows indicate a winnowing of grain-size fractions. Arrows that become broader in the indicated direction represent a coarsening upwards of the grain-size of the surficial sediments; arrows narrowing in that direction are representative of a fining trend. The dashed small arrows are indicative of a washing out of the finest fractions. These can easily be carried away with the flow. The straight arrows in the swales show that some fractions are bypassed and do not interact with the sandbanks.

From the distribution pattern of the surficial sediments, some hypotheses on sediment transport mechanisms can be deduced:

Regional sediment transport

Within the same morphological unit (i.e. sandbank, swale) the surficial sediments progressively become finer in the direction of the flood residual current (SW-NE). As this trend is independent of the tidal cycle, it can be concluded that on a regional level the area is flood-dominated; sediment transport is thus preferentially in a northeastern direction. This trend is however biased by superimposed processes.

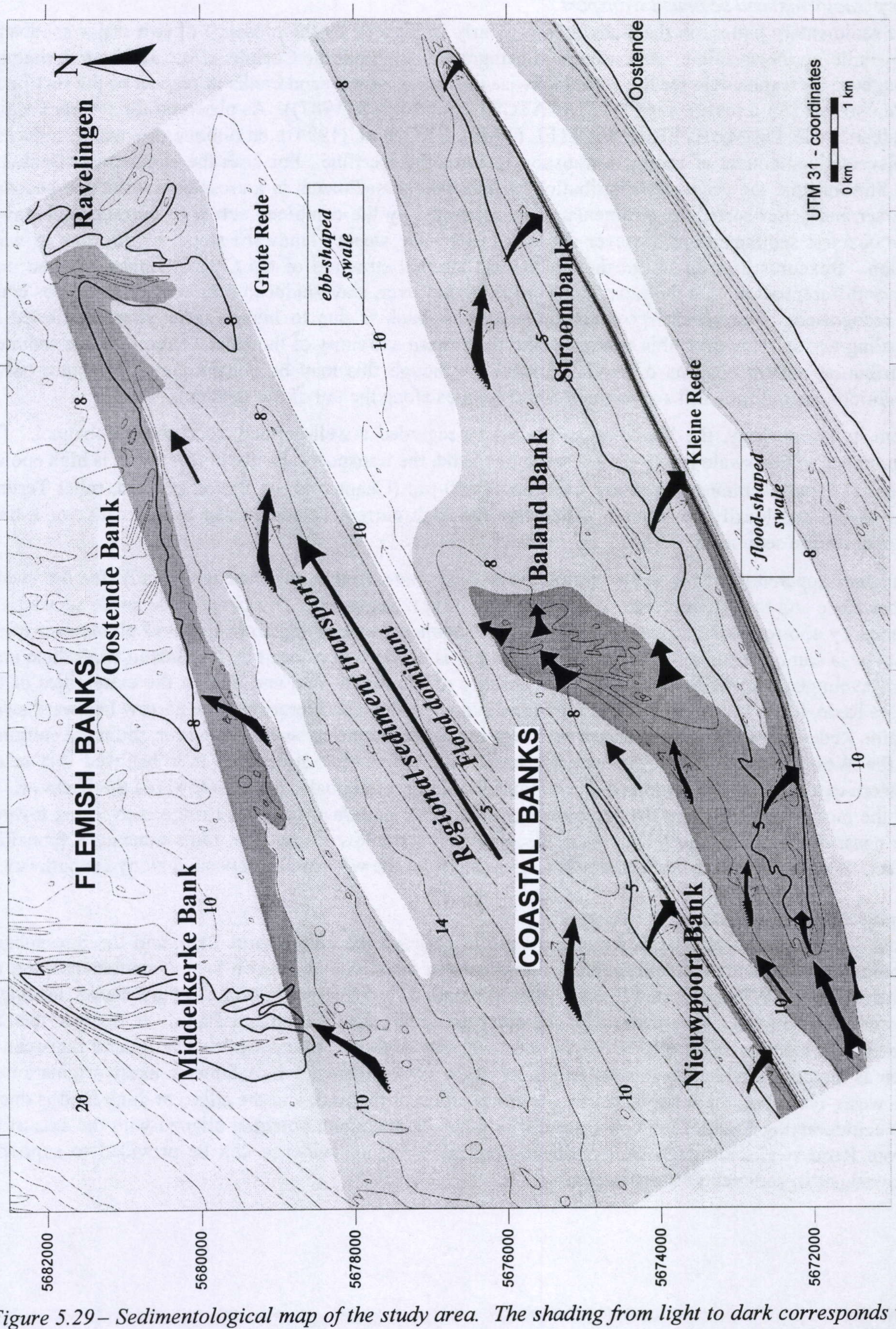


Figure 5.29 – Sedimentological map of the study area. The shading from light to dark corresponds with surficial sediments having a mean grain-size within the range of respectively very fine (62.5-125 μm), fine (125-250 μm) and medium (250-500 μm) sand. The arrows indicate the sediment transport pathways inferred from grain-size characteristics (compilation of field data).

Morphology induced sediment transport
The sedimentary pattern in the study area is clearly influenced by the presence of two major sandbanks subparallel to the coastline. As outlined in paragraph 5.2.2, both the Coriolis effect and bottom drag are thought to be responsible for the anti-clockwise deflection of the sand banks in respect to the rectilinear tidal currents (for a review see PATTIARATCHI & COLLINS (1987)). As observed for several Belgian sandbanks (i.e. DE MAEYER & WARTEL (1988), GAO et al. (1994)), an oblique orientation induces a transversal component of sediment transport towards the crestline. For both the Nieuwpoort Bank and the Stroombank, the grain-size distribution of the surficial sediments in a cross-bank direction becomes coarser and better sorted, as sedimentation is generated by the combined action of currents and waves. The coarsest sediments are however deposited along the steeper landward slope, mainly due to wave action. Boxcores used to reveal the small-scale internal structure of the Coastal Banks, showed only minor differentiation. On the most landward ridge however, wave-induced sedimentary structures could be recognised. The general coarser texture of this bank is due to higher shear stresses exerted by shoaling waves. However, this contrasts with the eastern extremity of the bank. Therefore, the sediment distribution pattern consists of sand and mud. Although this may be contemporary in nature (when conditions are mild), it still shows the lesser dynamics along the tail of the sandbank.

From its morphology, the Westdiep swale can be regarded a well-defined flood-shaped channel. The importance of this swale is two-fold. On the one hand, the transport capacity of this swale is high enough to entrain coarse-grained sediments, even up to 400 μm (Chapter 4); on the other hand, relict Tertiary clay layers can locally be eroded. Therefore the high current velocities can be the cause of a huge amount of fine sediments.

Although apparently of the same texture (very fine sands, highly enriched with mud), for the swales Grote Rede and the Kleine Rede, a different evolution is supposed. The Grote Rede swale seems to be shaped by ebb-residual currents, suggesting that sediments originating from the mud plume east of the study area can be deposited. Its distribution pattern is however constraint by the Baland Bank dune area, the Ravelingen and the Stroombank. The absence of the facies sand and mud at the extremities of the Grote Rede, likely indicates a funnelling effect and an upslope acceleration. The narrow landward swale Kleine Rede can be seen as a southern prolongation of the Westdiep swale. However, sediment entrained in the Westdiep swale will preferentially be transported in that direction. It is believed that at the western extremity of the Stroombank, the finer fraction preferentially deviates towards the Kleine Rede. As the most landward ridge the Stroombank is a former shoreface-connected ridge converging towards the coast at Oostende, the Kleine Rede becomes more shallow to the east, thus inducing a funnelling effect. It seems plausible that sediments originating from the west can be deposited along the pathway.

Topography induced sediment transport
Most peculiar is the presence of medium sand in between the Nieuwpoort Bank and the Stroombank, prolonging towards the Baland Bank in a northeastern direction. As shown in the previous chapter, the velocity of the SW-NE oriented flood current increases as it converges in between those banks, leading to deposition of coarser sediments near the divergent point, i.e. the Baland Bank. It is clear that the presence of medium sand reflects the transport capacity of the Westdiep swale. The Baland Bank can be seen as the parabola-shaped, eastern extremity of the swale; therefore its sediments likely originate from the west. However, the relative stability in the position of the bank and the adjacent dune field is due to the counteracting force of the ebb-current which has its maximum potential aligned with the axis of the Grote Rede swale, although on a sedimentological basis, no evidence can be provided to support a provenance of sediments from the east.

5.4. Conclusion

5.4.1. Sediment transport pathways inferred from morpho-sedimentological evidence

From the seabed topography and morphology and its sedimentological characteristics, some deduction can be made of the sediment and morphodynamics in the near coastal area. Figure 5.30 is a compilation of the results presented throughout this chapter.

The morphological and the sedimentological results lead to the same conclusions. Striking is the correlation of the presence of bedforms in the area where medium-grained surficial sands are present. The boundary with the fine-grained surficial sediments is sharp, as is the difference in dynamics. Along the southern part of the Middelkerke Bank very large dunes of more than 2 m in height do occur in an area characterised by fine surficial sediments. The same holds true along the Ravelingen. This demonstrates that it is merely the shallowness of near coastal zone that is a limiting factor in bedform development.

A flood dominant regional sediment transport is found throughout the area. This matches with the sediment transport calculations presented in Chapter 4. As well from bedform evidence as from the surficial grain-size characteristics, it is clear that generally only the area shallower than - 8 m is indicative of higher dynamics. Deeper, hardly any bedforms can be observed and the surficial sediments become finer and more poorly sorted. Moreover, the sediments are most likely to be enriched with mud, possibly deposited from the surficial waters during the turning of the tides. Deposition of mud may even occur somewhat deeper than - 6 m, except for areas with higher dynamics due to their configuration. The presence of trawl marks is common.

Although the flood controls the transport of sediment, a transversal differentiation in sediment transport is apparent in the sandbank areas. Small to medium dunes and at some locations even larger dunes occur along the slopes from the swales towards the sandbanks. Their morphology indicates an upslope transport of sediments. This process was clearly confirmed by the differentiation in grain-size. It should be noted that such evidence was found for as well the gentle as the steep slopes of the sandbanks, though hardly any upclimbing ripples were seen along the gentle slopes. The transversal differentiation is mainly due to the bottom drag and the Coriolis force, mostly affecting the gentle slope of the sandbanks.

Both the morphology and the surficial sediments clearly demonstrate the enhanced dynamics along the Westdiep swale where both the Nieuwpoort Bank and the Stroombank interact. Very large dunes are observed along the slope and on the western extremity of the Stroombank, and a strong differentiation in grain-size is observed. Winnowing of the finer fractions is intense. Also, the presence of patches of bioclastics in the lee side of the dune-like structures is an indication of the turbulent flow in this zone.

Most peculiar are the Baland Bank and the dune field east of it. The presence of the sandbank is however two-fold. On the one hand, it seems clear that the existence of the sandbank corresponds with a global decrease in tidal currents after having funnelled through the Westdiep swale. On the other hand, the morphology and the sedimentological characteristics seem to indicate an intense interaction between the tidal currents and the available sand. The morphology of the dune field and the progressive fining trend in the area seem to correspond with a gradually decreasing shear stress along the area. It should be noted that the supposed funnelling effect in the Westdiep swale could not be fully proven from the available current meter data (Chapter 4), though compared to neighbouring stations, the flood current is rectified and its timespan is increased with two hours. This largely favours an input of sediment towards the Baland Bank. From the morphology of this small sandbank, it should be concluded that the counteracting forces of the ebbing tide should not be underestimated, although nor from the bedform evidence, nor from the sedimentological characteristics this could be proven. This is in contrast to the southern part of the Middelkerke Bank and the Ravelingen. Although these sandbanks predominantly testify of the dominance of the flood current, a clear influence of the ebb tidal current is apparent, as well morphologically as sedimentologically.

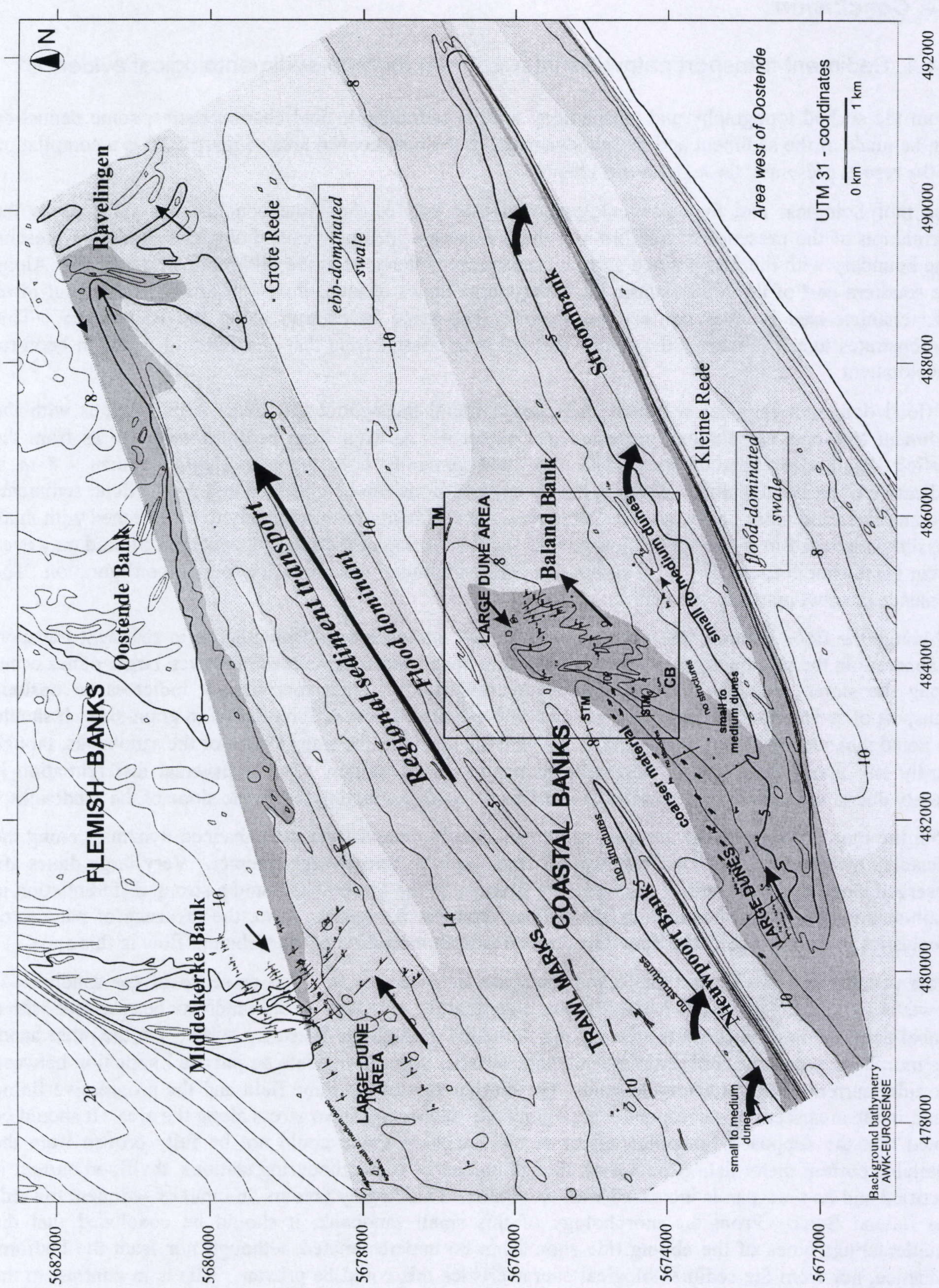


Figure 5.31 – Cartoon of sediment and morphodynamics in the near coastal area based on a compilation of a general sedimentological map and bedform characteristics. The shading from light to dark corresponds with surficial sediments having a mean grain-size within the range of respectively very fine (62.5-125 µm), fine (125-250 µm) and medium (250-500 µm) sand (Compilation of data).

A circulation of sand around the sandbanks can neither be proven from the morphological nor from the sedimentological evidence. From the tide-topography interaction including the Coriolis force, a circulation in a clockwise direction would be most likely (KENYON et al. (1981)). This means that the landward slope of the sandbanks would be characterised by a residual sediment transport in a roughly southwestern direction. However, as the landward slopes are constrained by flood dominated swales having a high sediment transport capacity, the residual forces would be highly counteracted. Moreover, at the western extremities of the sandbanks, the flood current determines the morphology of the landward flank; even the crest witnesses the dominance of the flood current.

The general dynamics of the shoreface correspond with the trends observed along the sandbanks. As well its morphology as the differentiation of the surficial sediments demonstrate an upslope transport of sediments, also enhanced by the Coriolis force. Although the dynamics of a shoreface is generally high due to the complex current-wave interaction, a complete homogenised sedimentary facies is only found from a level of - 5 m.

5.4.2. Comparison with other coastal systems

The facies distribution in the near coastal area clearly differs from that of the Flemish Bank area. This dissimilarity is mainly due to the nature of the sediments, the difference in the source of sediments and the increasing influence of wave activity in a shoreward direction. The difference is not solely due to the importance of wave activity, as shallower regions of - 5 m also occur on the Flemish Banks; still the sedimentary pattern remains fairly differentiated and its build-up may reflect both tidally- and wave-induced sedimentary structures. In the Flemish Bank area the flood and ebb currents are more competent, giving the potential for the formation of small- to medium dune cross-bedding (LANCKNEUS (1989), HOUTHUYS (1990); STOLK (1996)). Apart from the high-angle cross-bedding at the crests of the sandbanks, the troughs in the Flemish Bank area are completely bioturbated and thus witnessing quiet conditions (HOUTHUYS (1990), STOLK (1993)).

The differences with the Flemish Banks can be summarised as follows:

- the sedimentary pattern in the near coastal area is more homogeneous than the facies encountered on the Flemish Banks;
- deeper than roughly - 6 m, the surficial sediments of the near coastal area are likely enriched with mud;
- similar to the Flemish Bank area, a clear differentiation in processes exists between the sandbank's crest and troughs; generally, the surficial sediments in the Flemish Bank area are coarser at the crest of the sandbanks and finer in the troughs;
- in contrast to the Flemish Banks, the coastal Nieuwpoort Bank and the Stroombank do not show any cross-bedding; only along the steep slope of the banks a faint layering can be observed; still low-angle and horizontal bedding, as would be expected as a result of wave action, seems to be rather scarce;
- although the swales closer to the coast may be bioturbated under calmer conditions, they also witness an important input of sediment, including coarse-grained material; they are intermittently active;
- the sedimentary sequences of the southern part of the Middelkerke Bank resemble those of the Coastal Banks;
- the Oostende Bank is very rich in shelly material; this might be due to a richer fauna or to a weaker sediment transport.

More striking is the difference with the shoreface-attached ridges along the central Dutch coast. On the basis of 250 boxcores, VAN DE MEENE (1994) and VAN DE MEENE et al. (1996) studied in detail the sedimentary sequences in the inner shelf ranging in depth from - 14 to - 20 m. The cores were dominated by low-angle bedding or cross-bedding, showing frequent lateral transitions from high- to low-angle laminae in combination with irregular erosion planes. Due to the continuous alternations of tidal current- and wave-related features, they defined them as the combined flow facies. The bedforms created by a 'combined' flow form a polygenetic group, with currents driven by a combination of mechanisms (tidal currents, density- or wind-driven currents, wave-orbital motions). The features representative of such a facies, are less developed than would be expected for purely tide- or wave-formed deposits. The dominance of the combined flow deposits, in combination with the relative scarcity of bioturbated cores, led them to the conclusion that the seabed is frequently being reworked under the present hydrodynamic conditions. Although no spatial variation could be established related to the ridges, the combined flow deposits appeared to be concentrated in a zone relatively close to the coast. The increased wave influence also inhibited the formation of bedforms.

Although VAN DE MEENE et al. (1996) described the sedimentary sequences as being homogeneous, they contrast with the observations along the Belgian near coastal area. It is believed that the latter also correspond to the combined flow facies, though evidence of both tidally and wave-related features are hard to distinguish and the effect of the tides seems to predominate. Unlike the observations of VAN DE MEENE (1994), the relationship between the sedimentary structure, the grain-size and morphology seems to be more related in the Belgian near coastal area. This seems to be due to the shallowness of the area. As also postulated by VAN DE MEENE (1994), it may be very difficult to recognise the combined flow facies in the fossil record due to its rather undifferentiated nature.

SWIFT et al. (1986) found systematic trends in the sedimentary structures of the storm-dominated ridges on the American Atlantic shelf. Lag deposits, indicating erosion, were found in the troughs, while high-angle cross-bedding, reflecting the dominance of current action, was found in the troughs and on the coarser-grained up-current flanks. Low-angle cross-bedding and low-angle parallel lamination and graded beds, indicative of the dominance of wave action, were found on the crests and at the seaward flanks of the banks.

A better sorting of the sediments at the crests is found in most sandbank complexes. The increased sorting coefficient means that as well the finest as the coarsest fractions are missing, which is attributed to a net transport from the troughs towards the crests (VAN DE MEENE (1994)). This is the case for the Flemish Banks (LANCKNEUS (1989), HOUTHUYS (1990), TRENTESAUX et al. (1994)), the Norfolk Banks (McCAVE & LANGHORNE (1982)), the Scarweather Sands (PATTIARATCHI & COLLINS (1987)), the shoreface-connected ridges along the Dutch coast (VAN DE MEENE (1994)) and along the East Frisian coast (ANTIA (1996)). Normally, the mean grain-size is also finest along the crest, though this trend seems to be variable depending on the dynamics of the area. On the Scarweather Sands (PATTIARATCHI & COLLINS (1987)) and on the East Frisian ridges (ANTIA (1996)), the sediments are finer at the ridge crests and coarser in the troughs, whilst in the Flemish Bank area the crest is mainly characterised by coarser surficial sediments (LANCKNEUS (1989), HOUTHUYS (1990), TRENTESAUX et al. (1994)).

In the literature, speculations on the behaviour of a sandbank system on a longer time-scale may be deduced from the general differentiation in grain-size along those systems. HOUTHUYS (1990) mentions a fining of surficial sediments in a landward direction in the Flemish Bank region. From the observations presented throughout this chapter and from the literature, it seems clear that the Coastal Banks tend to be accretional in a landward direction. This is supported by the hydrographic analysis of VAN CAUWENBERGHE (1971), the seismic profiles presented by HENRIET & DE BATIST (1983), DE MAEYER et al. (1985), WARTEL (1988) and the sedimentological observations of DE MAEYER & WARTEL (1988).

Nevertheless, a fining trend in a seawards direction was found by VAN DE MEENE (1994) for the shoreface connected ridges, across linear ridges on the American Atlantic shelf (SWIFT et al. (1986)) and along the shoreface-connected ridges on the East Frisian shelf (ANTIA (1996)).

5.5. Summary

From the spatial geo-acoustical and sedimentological differentiation, an interactive fair-weather sediment transport model is proposed. Water movement, sand transport and morphology seem to be in continuous interaction, pleading for a morphodynamically coupled system.

The combined action of currents and waves determines the sedimentary pattern on the sandbanks. The rather homogenised nature of their morphology is mainly due to active sorting processes. Although the swales are only intermittently active, it is believed that they are the key element in the functioning of the coastal system. Especially when tidal currents are funnelled, sandy deposits are being washed out towards the slopes of the banks. Part of the accumulated sediments can subsequently be winnowed out and transported upslope the sandbanks, whereby the fining upwards trend is mainly tidally driven. In water depths shallower than roughly - 5 m, waves play an important role, washing out the fines and entraining the coarser fraction, which is ultimately deposited along the steep slope. This means that waves, at least, actively take part in the maintenance of the sandbanks. The current velocity in the swales is high enough to transport sediments, meaning that any landward migration of the banks would be counteracted by the transport capacity within the swales.

6. RESULTS: TEMPORAL VARIABILITY OF A COASTAL SYSTEM

6.1. Introduction

The inner-shelf morphology and its associated sedimentary processes are predominantly influenced by the tidal currents. However, forces imposed by wind and wave regimes become more important with decreasing water depths (WRIGHT (1995)).

The gradients in sediment transport that cause morphological change exist on a hierarchy of time and space scales (WRIGHT (1995)). In literature, those scales have been defined in various ways and from different perspectives. Distinctions can be made among 'instantaneous', 'event', 'medium-term' and 'geological' timescales (COWELL & THOM (1994), DE VRIEND et al. (1993)). Models that address instantaneous and event-scale morphological responses are typically deterministic, in the sense that they time-integrate the fundamental flow, bed stress and transport equations across the inner-shelf (COWELL & THOM (1994); DE VRIEND et al. (1993)). A higher degree of parameterisation is required for modelling of decadal timescale changes or geological evolution of depositional morphology (COWELL & THOM (1994)).

Since the early 90's, research became more and more focussed on large-scale coastal behaviour with the aim of understanding coastal and nearshore sedimentary systems, and correspondingly the prediction of changes occurring within these systems (LIST & TERWINDT (1995)).

In the framework of the present study, the spatial variability of the coastal system has been described 'as a whole' and in some detail for the zones witnessing higher dynamics. However, the need is felt to evaluate the observations in time, and hence to deduce the behaviour of the coastal system under a variety of conditions. This has been done on three scales, chosen according to the response time needed to adjust to changes in the hydraulic regime. In the present chapter, 'short-term' is used, referring to the action of hydraulic sorting processes, distinguished on the basis of grain-size characteristics through time. With 'medium-term' morphological change, changes in the inner shelf morphology will be explained in terms of accretion and/or erosion of sediments. The observations will be linked to hydro-meteorological variations, likely having a large seasonal component. Finally, 'long-term' morphological change will be discussed focussing on the geological evolution of the coastal system in the light of the rising sea-level. From this, some prediction will be made for its future evolution.

The understanding of the interaction between morphological changes and hydro-meteorological conditions can be of paramount importance for dredging purposes as for coastal management problems in general (LIST & TERWINDT (1995)). An unravelling of such an interaction can lead to a better evaluation of erosive events along the coast and may help in selecting the type of engineering works needed to protect the coast .

6.2. The hydro-meteorological database as the missing link in morphological change

In order to explain the morphology of the areas and the changes between successive campaigns, all observations are coupled to hydro-meteorological data provided by the *Belgian Waterways Coast Division.* This allows primarily to study the sensitivity of the areas to changes in the wind and wave climate, that eventually might lead to a deduction of the most vulnerable conditions.

6.2.1. Characterisation of the Belgian wind climate

On the basis of multi-annual observations (1977 – 1986) of the wind climate along Zeebrugge (Fig. 2.08), winds from a SSW to SW direction associated with a Beaufort number of 3 to 4, have the highest frequency of occurrence (MINISTERIE VAN DE VLAAMSE GEMEENSCHAP (1993)). Winds of more than 6 Bf generally blow from a WSW to NW direction or are generated from the NE.

The wind climate throughout the study period has been yearly characterised in the Figures 6.01 and 6.02. Generally, the average wind speed varied around 11 – 12 Knots corresponding to 4 Bf with a dominant wind direction from the SW. Interesting was the counteraction of NE winds. These winds were even equally important in 1996 and 1997. The figures of 1998 are fully dominated by SW winds, but they only represent the period of January to May. The average wind speed was hence somewhat higher.

A wind speed of more than 6 Bf is likely to occur from a SW direction, though in 1996 the highest frequency corresponded to NNE winds. Still, a NW direction is often the most devastating one (MINISTERIE VAN DE VLAAMSE GEMEENSCHAP (1993)).

In order to determine the seasonal variation in morphological change, wind data per season were extracted from the hydro-meteorological database and presented in wind roses (Fig. 6.03).
It can be deduced that the winter months are generally characterised by strong SSW to SW winds. Remarkable is the winter of 1996-1997, when winds blew predominantly from an eastern direction. The spring period seems to be generally characterised by SW and NE winds, but with an important contribution of more than 6 Bf N to NE winds. Although the summer months represent the calmest conditions, the summer of 1995 was clearly influenced by NE to NNE winds, whilst the characteristics of the summer of 1996 were biased by a stormy period (NW-NNW) at the end of August. The autumn period resembles the winter characteristics, though the wind speed is generally not as high. Although this pattern could not be evaluated on a multi-annual basis, the trends resemble the variations found along the area of Dunkerque (FR) in the period 1951- 1960 and 1990 – 1994 (in CORBAU et al. (1999)).

A study of the wind climate in relation to tidal currents along Dunkerque (FR) (CORBAU et al. (1999)) showed that the flood or ebb tidal phase may be delayed or prevented by wind action. From the observations, the spring flood current seemed to be delayed by NE winds, whilst SW winds have such an effect on the spring ebb current. Acceleration of the tidal currents by wind action was deduced. Along the SE slope of the Middelkerke Bank, STOLK et al. (1996) also showed a suppression of the ebb tidal current by persistent SW winds.

6.2.2. Characterisation of the Belgian wave climate

Multi-annual calculations (1977 – 1982) of the wave parameters of a near coastal wave buoy, show that waves of 0.50 – 1 m high and a period of 3.5 – 4.5 s have the highest frequency of occurrence (MINISTERIE VAN DE VLAAMSE GEMEENSCHAP (1993)). Along the offshore station Westhinder (Hinder Banks, Fig. 1.01), waves of 1 to 2 m in height are most common and are most frequently generated from a SSW to SW direction (1977 – 1988). N to NE waves occurred about 10 % of the time (VOULGARIS et al. (1998)). Waves, having a height of more than 3 m generally have a W to WNW direction (MINISTERIE VAN DE VLAAMSE GEMEENSCHAP (1993)).

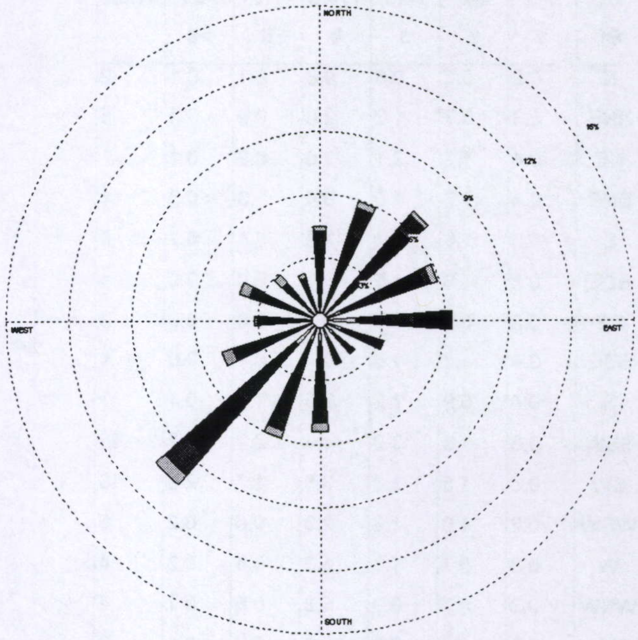
Table 6.01 – Maximum and average wave heights for the locations Oostende, Trapegeer and Westhinder in the period August 1997 till May 1998. (Source data: AWK) (for location see Fig. 1.01) (Max: maximum, Avg: average).

	Oostende		Trapegeer		Westhinder	
Sector	Max (m)	Avg (m)	Max (m)	Avg (m)	Max (m)	Avg (m)
N – E	3.64	0.56	3.25	0.56	4.15	1.16
E – S	1.25	0.26	1.38	0.28	2.88	0.73
S – W	2.20	0.55	2.10	0.55	4.36	1.22
W – N	3.55	0.92	3.33	0.80	5.20	1.37

1995 - Period 01/01/1995 – 31/12/1995

Frequency distribution (normalised)

Kt	1-3	4-6	7-10	11-16	17-21	>21	Total
Bf	**1**	**2**	**3**	**4**	**5**	**>6**	
N	0.1	0.6	1.0	1.7	0.8	0.3	4
NNE	0.2	0.4	1.1	2.7	1.4	0.3	6
NE	0.2	0.6	2.0	2.9	1.0	0.2	7
ENE	0.2	0.9	2.1	2.1	0.3	0.3	6
E	0.2	1.5	2.8	1.7	0.1	0.0	6
ESE	0.2	0.9	1.6	0.5	0.0	0.0	3
SE	0.1	0.7	1.1	0.2	0.1	0.0	2
SSE	0.3	0.7	0.9	0.4	0.1	0.0	2
S	0.2	0.8	1.3	2.0	0.7	0.4	5
SSW	0.2	0.9	1.8	2.0	0.7	0.4	6
SW	0.2	1.4	**3.7**	3.2	1.2	0.6	10
WSW	0.1	0.4	1.3	1.8	0.8	0.6	5
W	0.1	0.5	1.1	1.1	0.3	0.2	3
WNW	0.2	0.5	1.0	1.2	0.8	0.5	4
NW	0.2	0.6	0.6	0.6	0.4	0.5	3
NNW	0.1	0.4	0.6	0.8	0.3	0.3	2
Total	3	12	24	25	9	5	77

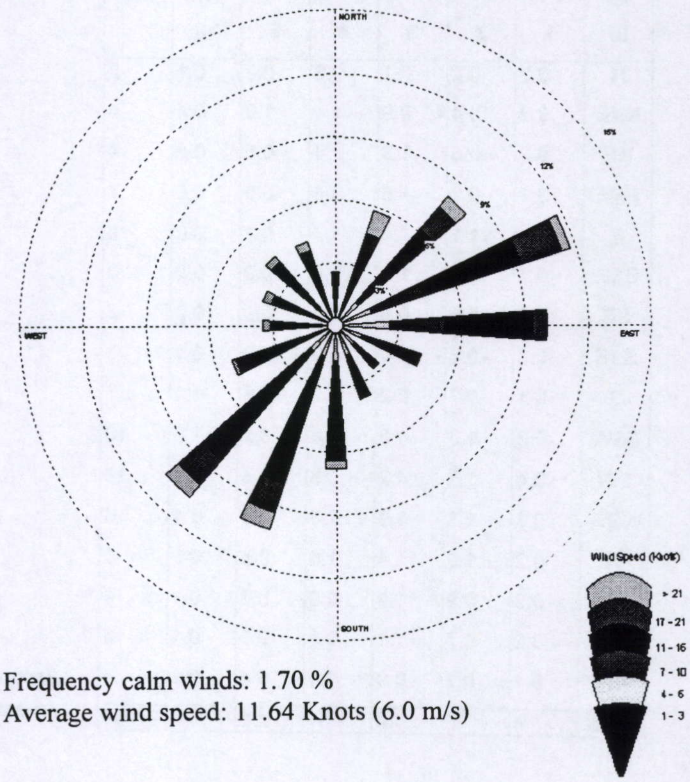


Frequency calm winds: 23 %
Average wind speed: 11.44 Knots (5.9 m/s)

1996 - Period 01/01/1996 – 31/12/1996

Frequency distribution (normalised)

Kt	1-3	4-6	7-10	11-16	17-21	>21	Total
Bf	**1**	**2**	**3**	**4**	**5**	**>6**	
N	0.1	0.5	0.9	0.9	0.2	0.1	3
NNE	0.1	0.6	1.0	2.2	0.9	1.1	6
NE	0.4	1.0	2.4	2.3	1.4	0.6	8
ENE	0.4	1.4	2.6	**4.8**	2.0	0.4	12
E	0.6	2.0	2.6	4.2	0.7	0.0	10
ESE	0.4	1.0	2.0	0.9	0.0	0.0	4
SE	0.3	0.9	1.0	0.4	0.1	0.0	3
SSE	0.4	1.1	1.4	0.7	0.1	0.0	4
S	0.5	1.3	1.8	2.0	0.9	0.4	7
SSW	0.3	1.3	3.0	3.3	1.5	0.9	10
SW	0.3	1.3	2.9	3.9	1.5	0.8	11
WSW	0.2	0.6	1.2	2.3	0.7	0.2	5
W	0.2	0.6	0.8	1.0	0.5	0.4	4
WNW	0.2	0.5	0.9	0.9	0.7	0.4	4
NW	0.2	0.8	1.2	1.5	0.4	0.4	4
NNW	0.2	0.6	1.2	1.4	0.5	0.5	4
Total	5	15	27	33	12	6	98



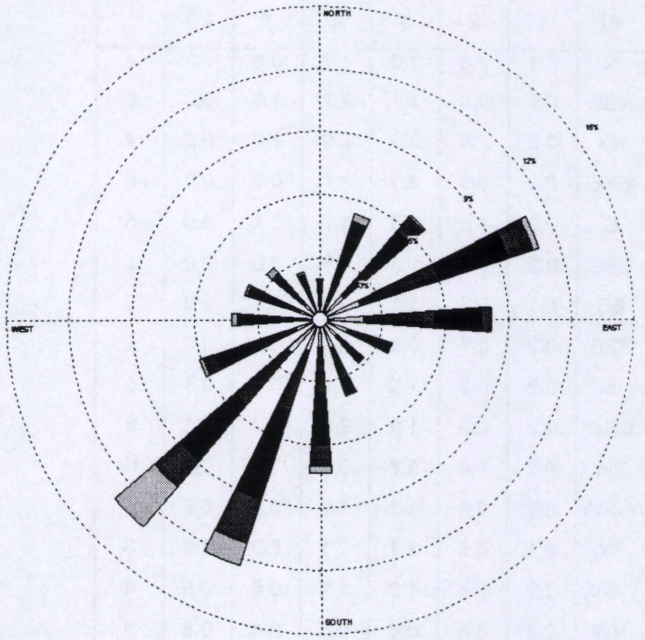
Frequency calm winds: 1.70 %
Average wind speed: 11.64 Knots (6.0 m/s)

Figure 6.01 - Frequency distribution of wind characteristics in the period January – December 1995 (A) and January – December 1996 (B) (Source data AWK).

1997 - Period 01/01/1997 – 31/12/1997

Frequency distribution (normalised)

Kt	1-3	4-6	7-10	11-16	17-21	>21	Total
Bf	1	2	3	4	5	>6	
N	0.2	0.5	0.6	0.6	0.1	0.1	2
NNE	0.3	0.7	1.2	2.0	0.9	0.4	5
NE	0.4	1.2	2.1	2.0	0.9	0.1	7
ENE	0.4	1.7	4.0	3.4	1.3	0.3	11
E	0.5	1.6	3.4	2.2	0.4	0.1	8
ESE	0.5	1.0	1.5	0.7	0.0	0.0	4
SE	0.3	0.8	1.1	0.7	0.0	0.0	3
SSE	0.4	1.1	1.6	0.7	0.1	0.0	4
S	0.4	0.9	2.2	2.5	1.0	0.4	7
SSW	0.3	1.3	3.0	**4.4**	2.2	1.2	12
SW	0.6	1.5	3.3	3.5	1.7	2.5	13
WSW	0.2	1.0	1.8	2.3	0.6	0.2	6
W	0.3	0.7	1.3	1.3	0.4	0.3	4
WNW	0.3	0.7	0.9	1.2	0.6	0.1	4
NW	0.3	0.7	0.9	0.8	0.3	0.4	3
NNW	0.2	0.6	0.9	0.4	0.2	0.2	3
Total	6	16	30	29	11	6	97

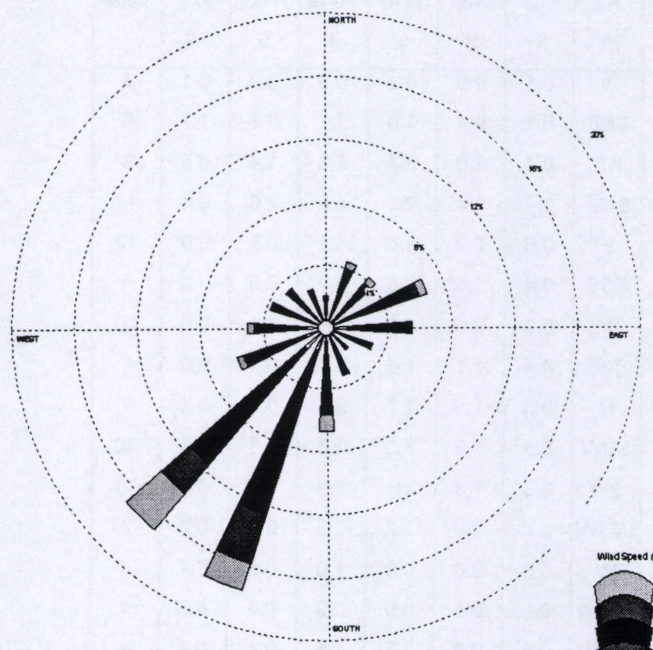


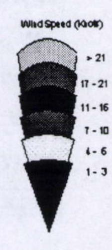
Frequency calm winds: 3 %
Average wind speed: 11.17 Knots (5.7 m/s)

1998 - Period 01/01/1998 – 31/05/1998

Frequency distribution (normalised)

Kt	1-3	4-6	7-10	11-16	17-21	>21	Total
Bf	1	2	3	4	5	>6	
N	0.2	0.2	0.7	0.6	0.3	0.1	2
NNE	0.2	0.4	0.9	1.4	1.2	0.4	4
NE	0.2	0.5	1.3	1.4	0.5	0.5	4
ENE	0.1	0.7	1.6	3.4	0.5	0.5	7
E	0.3	1.1	2.4	1.7	0.1	0.0	6
ESE	0.1	0.7	1.9	0.6	0.0	0.0	3
SE	0.3	0.6	0.9	0.3	0.0	0.0	2
SSE	0.3	0.6	1.4	0.8	0.2	0.1	3
S	0.1	0.7	2.2	2.2	0.6	1.1	7
SSW	0.3	1.3	4.6	**6.4**	3.2	1.8	18
SW	0.4	1.5	4.2	5.5	2.4	3.0	17
WSW	0.3	1.1	1.9	2.0	0.3	0.4	6
W	0.2	1.0	1.4	1.6	0.4	0.5	5
WNW	0.2	0.9	1.3	0.9	0.3	0.1	4
NW	0.2	0.7	1.1	0.8	0.5	0.1	3
NNW	0.1	0.2	0.9	1.1	0.4	0.1	3
Total	4	12	29	31	11	9	94





Frequency calm winds: 5.70 %
Average wind speed: 12.20 Knots (6.3 m/s)

Figure 6.02 - Frequency distribution of wind characteristics in the period January – December 1997 (A) and January – May 1998 (B) (Source data AWK).

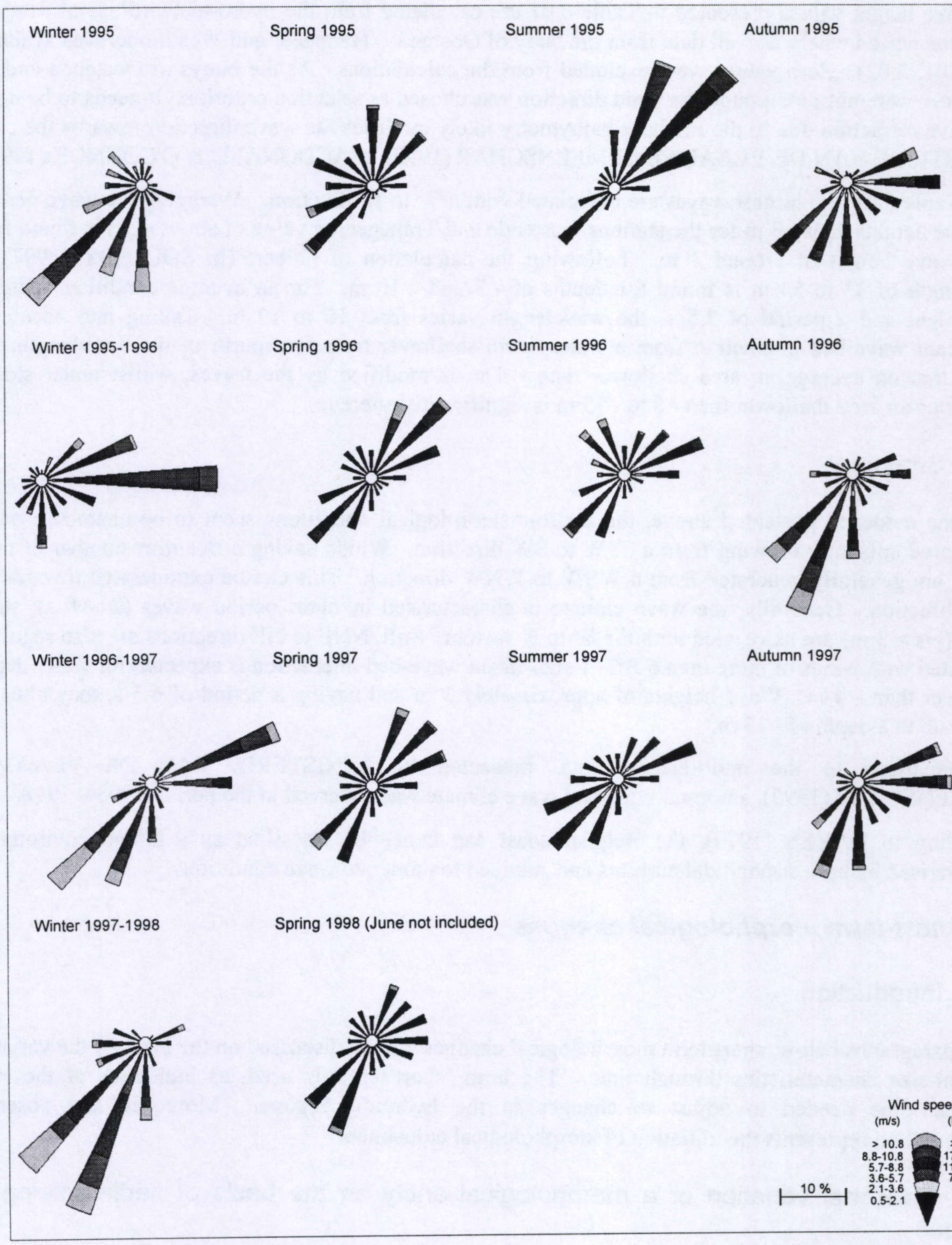


Figure 6.03 - Seasonal variation in the wind climate (winter 1995 to spring 1998) (Source data AWK).

The wave height values presented in Table 6.01 are calculated from the hydro-meteorological database for a time period where as well data from the buoy of Oostende, Trapegeer and Westhinder was available (Fig. 1.01, 2.02). Zero values were excluded from the calculations. As the buoys of Oostende and the Trapegeer were not directional, the wind direction was chosen as selection criterion. It needs to be noted that wave refraction due to the offshore bathymetry likely modifies the wave direction towards the coast (MINISTERIE VAN DE VLAAMSE GEMEENSCHAP (1993), MACDONALD & O'CONNOR (1996)).

From Table 6.01, the largest waves are associated with a W to N direction. Averaging the wave periods for wave heights above 3 m for the stations Oostende and Trapegeer, a value of about 6.5 s is found for a mean wave height of around 3 m. Following the calculation of Gilbert (In SOULSBY (1997)), a wavelength of 33 to 54 m is found for depths of - 3 and - 10 m. For an average condition of 0.5 m waveheight and a period of 3.5 s, the wavelength varies from 16 to 19 m. Taking into account a significant wave-bed interaction from a water depth shallower than one fourth of the wavelength, this means that on average an area shallower than - 4 m is modified by the waves, whilst under stormy conditions an area shallower than - 8 to - 13 m is significantly altered.

6.2.3. Summary

From the evidence presented above, the hydro-meteorological conditions seem to be characterised by winds predominantly blowing from a SSW to SW direction. Winds having a Beaufort number of more than 6, are generally generated from a WSW to WNW direction. This can be extrapolated towards the wave direction. Generally, the wave climate is characterised by short period waves (2 – 6 s); storm waves (Hs > 3 m) are associated with the W to N sectors. Still, NNE to NE directions are also regularly associated with winds of more than 6 Bf. A significant wave-bed interaction is expected for water depths shallower than - 4 m. Wave heights of approximately 3 m and having a period of 6.5 s, may alter the seabed up to a depth of - 13 m.

In comparison to the multi-annual data, presented by MINISTERIE VAN DE VLAAMSE GEMEENSCHAP (1993), a normal wind and wave climate was observed in the period 1995 – 1998.

According to HAYES (1979), the Belgian coast can hence be classified as a mixed environment characterised by both strong tidal currents and subdued to moderate wave conditions.

6.3. Short-term morphological changes

6.3.1. Introduction

In the paragraphs below, short-term morphological changes will be discussed on the basis of the variation in grain-size characteristics through time. The term 'short-term' is used, as indicative of the short response time needed to adjust to changes in the hydraulic regime. Moreover, the observed differentiation represents the initiation of morphological adjustment.

6.3.2. Seasonal variation of a morphological entity on the basis of sedimentological changes

6.3.2.1. Temporal variation in grain-size differentiation along the sandbanks

Throughout the study period, numerous samples of the surficial sediments of the different morphological entities have been taken; primarily to discuss the spatial variability of the coastal system (Section 5.3), but also to evaluate the temporal fingerprint of the samples. Table 6.02 is an overview of the sampling campaigns carried out on the shallow Coastal Banks, the Nieuwpoort Bank and the Stroombank. According to the time schedule, specific morphozones were selected for sampling.

One profile, covering both the Nieuwpoort Bank and the Stroombank has been sampled on a variety of occasions to validate the observed spatial grain-size variations throughout the seasons. Also, in a longitudinal sense those sandbanks have been sampled through time. From the sedimentological database, the samples belonging to the same morphozone have been selected for further temporal analysis.

Both the Baland Bank and the southern part of the Middelkerke Bank have at least been sampled twice, hence the differences in grain-size characteristics can be discussed.

Table 6.02 – Sampling campaigns comprising the Nieuwpoort Bank and the Stroombank during the period 1994 – 1998.

1994	1995	1996	1997	1998
		ST9601: Jan. 1996	ST9701: Jan. 1997	
		ST9603: Mar. 1996		
	ST9504: Apr. 1995	ST9604: Apr. 1996	ST9704: Apr. 1997	ST9804: Apr. 1998
	ST9505: May 1995			
	ST9506: Jun. 1995			
MB9407: Jul. 1994	ST9507: Jul. 1995			
	ST9508: Aug. 1995	ST9608: Aug. 1996	ST9708: Aug. 1997	
	ST9510: Oct. 1995			
	ST9511: Nov. 1995			
	ST9512: Dec. 1995			

Key: XXYYMM (i.e. MB9407): XX: internal prefix; YY: year of sampling; MM: month of sampling

Temporal variation in grain-size characteristics along the cross-transect Nieuwpoort Bank – Stroombank

The surficial sediments along a profile comprising both the Nieuwpoort Bank and the Stroombank has been sampled on 6 occasions in the period 1994 – 1998 (July 1994, July and December 1995, January 1996, August 1997 and April 1998). The points were chosen according to the boxcoring locations sampled in July 1994 (Fig. 3.03, Fig. 5.18). The differences in the mean and the sorting and the fractions are shown in Figure 6.04.

The differences in grain-size characteristics, as explained in Section 5.3.4.2, seem to be valid throughout the seasons, though some differentiation is observed according to the period of sampling. The difference in dynamics between the eastern part of the Nieuwpoort Bank and the western part of the Stroombank is clear.

The coarsest grains can be observed in the Westdiep swale and along the steep slope of the Stroombank. Grains from 1.00 ϕ (500 μm) onwards are enriched at the foot of the Stroombank. There they are gradually winnowed out and entrained upslope by the tidal currents, up to a depth of about - 5 to - 4 m in respect to MLLWS. It seems evident that this depth is dependant on the wave base (Section 6.2.2), hence seasonally determined. It is however clear that the volume percentages of the coarser grains in the Westdiep swales are highest during the winter and the spring season. It is apparent that the rougher the weather conditions, the higher the dynamics, hence the more coarse-grained material can be transported, though it is remarkable that the coarsest grains on the steep slope of the Stroombank are observed in the summer months. From this, it can be put forward that although the hydrodynamic sorting processes are valid throughout the seasons, more turbulence is expected during the winter months, entraining the grains further downslope, possibly combined with avalanching effects (SMITH (1988c)). Under calmer conditions the grains are still subject to the combined action of currents and waves, though the latter are only competent to transport the grains over the top of the banks or just seawards of the top, where SMITH (1969) calculated the highest shear stress. It seems also plausible that the coarsest grains reflect lag deposits. Moreover, the whole process of winnowing out, upslope entrainment and transport by currents and waves will last much longer under fair-weather conditions. This may explain the higher abundance of coarser grains at a level of - 5 m during the summer months. This process is valid for grain-sizes up to 1.75 ϕ (300 μm).

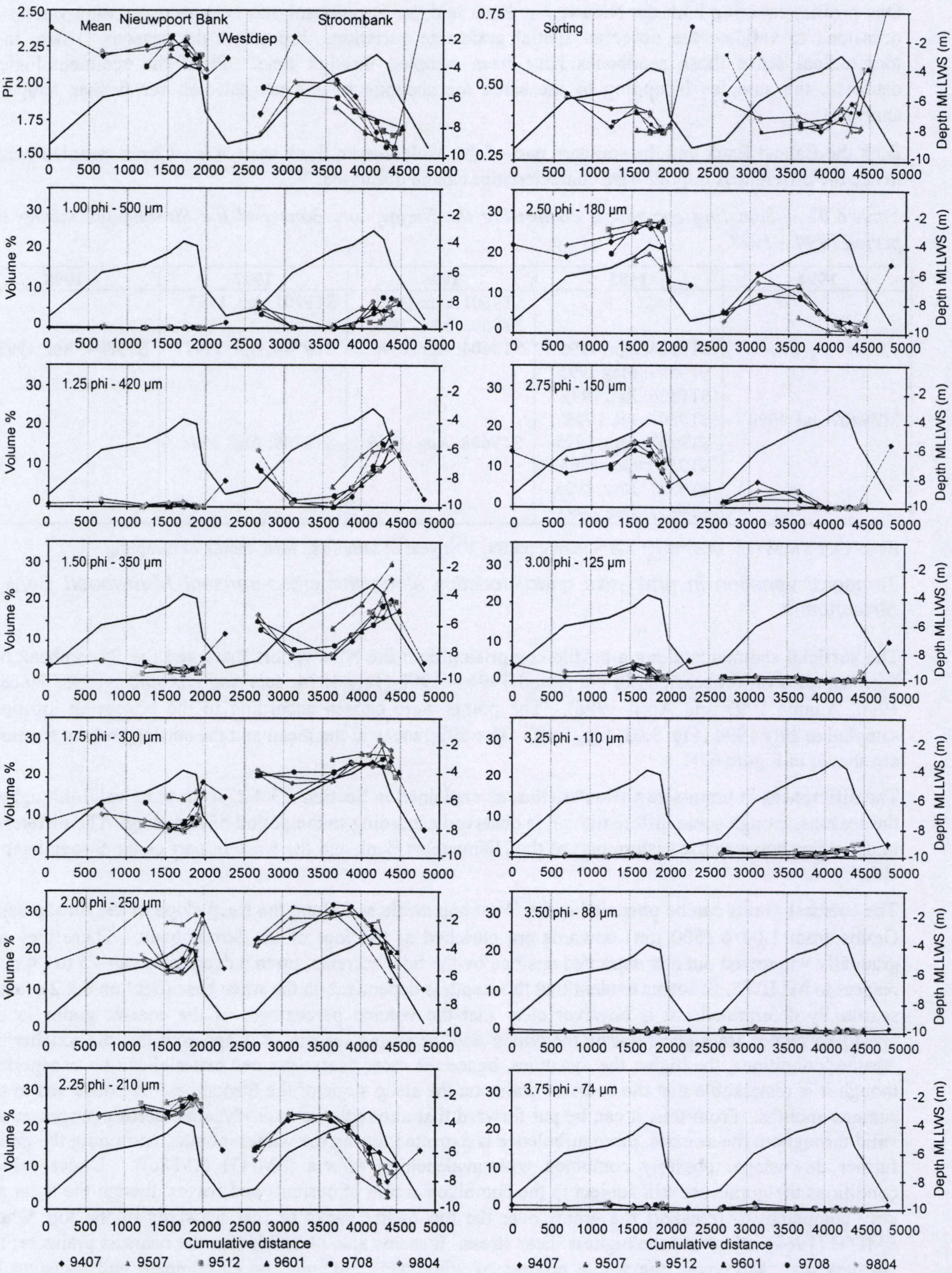


Figure 6.04 – Temporal variation of the grain-size fractions within the surficial sediments along a cross-transect comprising both the Nieuwpoort Bank and the Stroombank.

The dynamics along the Nieuwpoort Bank are less pronounced as the coarsest grains are being deposited just before the top of the bank. This corresponds with the findings of SMITH (1969). Much more scatter is found along the Nieuwpoort Bank. This may imply that there is no intense interaction between the seabed sediments and the hydrodynamic forces; hence, the surficial sediments may largely represent lag deposits. Still, along the top of the sandbank, grains of 300 to 210 µm are most abundant during the summer months; they are more easily washed out under rougher conditions.

From 2.25 to 2.00 ϕ (250 – 210 µm) grains are washed out along the Stroombank. The abundance of such grains is highest during the winter months. From the distribution pattern throughout the seasons, it seems that the rougher the conditions, the more sediments are entrained along the gentle slope of the sandbank, the more grains are washed out in the shallower regions. This trend is also valid for the Nieuwpoort Bank, though primarily for grain-sizes between 2.50 ϕ (180 µm) and roughly 3.25 ϕ (110 µm).

Surprisingly is the slight enrichment trend of grains around 3.25 ϕ (110 µm) from around the top towards the upper steep slope of the Stroombank under the different circumstances. It would be expected that this finer fraction would also be washed out and carried away with the current as is valid for the somewhat coarser grains. Moreover, this enrichment trend is most apparent during the winter period. It is believed that this fraction may be supplied by the Kleine Rede swale. The rougher the conditions, the more finer fractions are advected along that swale; these may interfere with the surficial sediments of the Stroombank.

Interestingly is the depletion of grains around 2.25 ϕ (210 µm) in the Westdiep swale; this seems to be valid throughout all seasons, meaning that the current in that swale is generally competent enough to transport grains of that size. This grain-size may become available as well in a longitudinal as in a transversal sense. Given the strength of the tidal current, the majority of the sediments will be transported along the swales.

Summary and conclusions:

- the different transport mechanisms, spatially observed along the morphological entities, are valid throughout the seasons; hence the observed trends are indicative for the maintenance of the sandbanks;
- the availability of sand fractions is dependent on the hydro-meteorological conditions: the rougher the conditions, the more grains are entrained upslope and the more sand can be deposited along its pathway; bias in the trends may be due to the weather conditions preceding the sampling campaigns; this will be discussed in the following section;
- the intensity of the hydrodynamic forces determines the deposition of sediment; under fair-weather conditions this trend is less pronounced;
- it is not clear to what extend the typical coarsening upward trend may also be preserved by lag deposits;
- entrainment of grains by the combined action of currents and waves is observed from 1.00 ϕ (500 µm) onwards for the Stroombank, and from 1.75 ϕ (300 µm) onwards on the Nieuwpoort Bank;
- for the Nieuwpoort Bank the threshold grain-size representative of entrainment by currents and waves and a washing out of these fractions, varies around 2.25 ϕ (210 µm); for the Stroombank this is valid around 1.75 ϕ (300 µm);
- the grain-sizes indicative of hydraulic sorting processes vary in the order of 0.25 ϕ;
- the observations correspond well with the calculations of sediment transport presented in Chapter 4.

Temporal variation in grain-size characteristics along the Nieuwpoort Bank and the Stroombank

To discuss the temporal variation in grain-size characteristics along the Nieuwpoort Bank, only a limited number of samples can be used. Along the steep slope of the sandbank, 7 representative locations (from W to E) were chosen that were sampled on three occasions: June 1995, August 1995 and April 1996. The first two graphs in the Figures 6.05 and 6.06 represent the mean grain-size of the surficial samples and the sorting. The other graphs show each fourth of phi fraction in the sample. The range 1.50 ϕ (350 µm) to 2.75 ϕ (150 µm) was chosen as being the most significant fractions to demonstrate grain-size differentiation.

From the variation in the mean grain-size, it seemed that the August 1995 samples were somewhat coarser in texture and had a poorer sorting than its counterparts sampled in June 1995 and April 1996. Looking at the grain-size fractions, the August 1995 samples are characterised by a higher volume percentage of the coarser fractions 1.50 and 1.75 ϕ (350 – 300 µm). Around 2.00 ϕ (250 µm), no consistent trend is found and from 2.25 ϕ (210 µm) onwards the April 1996 and June 1995 samples seemed to be more abundant in the finer fractions.

At first, it may appear unusual that samples taken during the summer months are coarser than those representing spring conditions, as one tends to associate coarser sediments with higher dynamics (VAN RIJN (1998)), though referring to the previous paragraph, this can be explained by a difference in intensity of the hydraulic sorting processes. The lesser abundance of the fractions 1.50 ϕ to 2.00 ϕ (350 – 250 µm) in the June 1995 and April 1996 samples can simply be explained by a winnowing out of these fractions by the combined action of currents and waves. The previous paragraph showed that for the lesser dynamic eastern extremity of the Nieuwpoort Bank, this process was reflected from 1.75 ϕ (300 µm) onwards. From the same evidence, a washing out of the finer fractions was expected from a grain-size of 2.25 ϕ (210 µm); hence the higher amount of those fractions present in the June 1995 and April 1996 samples correspond to more intense transport processes. This is also supported by a better sorting of the sediments of the latter campaigns. The coarser fractions in the August 1995 sediments likely represent lag deposits.

To demonstrate the temporal variability along the Stroombank, representative samples were chosen along the steep slope of the sandbank. A comparison can be made of surficial sediments sampled in May, October, November and December 1995.

The surficial sediments corresponding to the winter months are again finer and better sorted than their May counterparts. Analogous to the description given for the Nieuwpoort Bank, the coarser fractions are found in the sediments representative of a weaker dynamics, though the sediments sampled during the winter months are more abundant in the fractions from 2.00 ϕ (250 µm) onwards. As explained for the Nieuwpoort Bank, such a distribution pattern is indeed indicative of intenser hydraulic sorting processes during the winter months: coarser fractions are more easily entrained and finer fractions are more actively winnowed out and transported along the sandbank. Again, this is confirmed by a better sorting coefficient of the sediments representing the winter months.

It has to be noted that more bias is observed if samples are compared that are taken along the gentle slope of the sandbank. This morphozone is indeed less characterised by dynamic conditions than the more shallow regions. Thus their distribution pattern is not a good indicator of the intensity of the hydraulic sorting processes, which implies more randomness.

Summary and conclusions on the basis of all sampling campaigns

- during the winter months, the surficial sediments are finer and generally better sorted than during the summer months;
- the spring situation may resemble more to the summer characteristics of the surficial sediments;
- the results between the summer campaigns are more differentiated than the results between the winter campaigns.

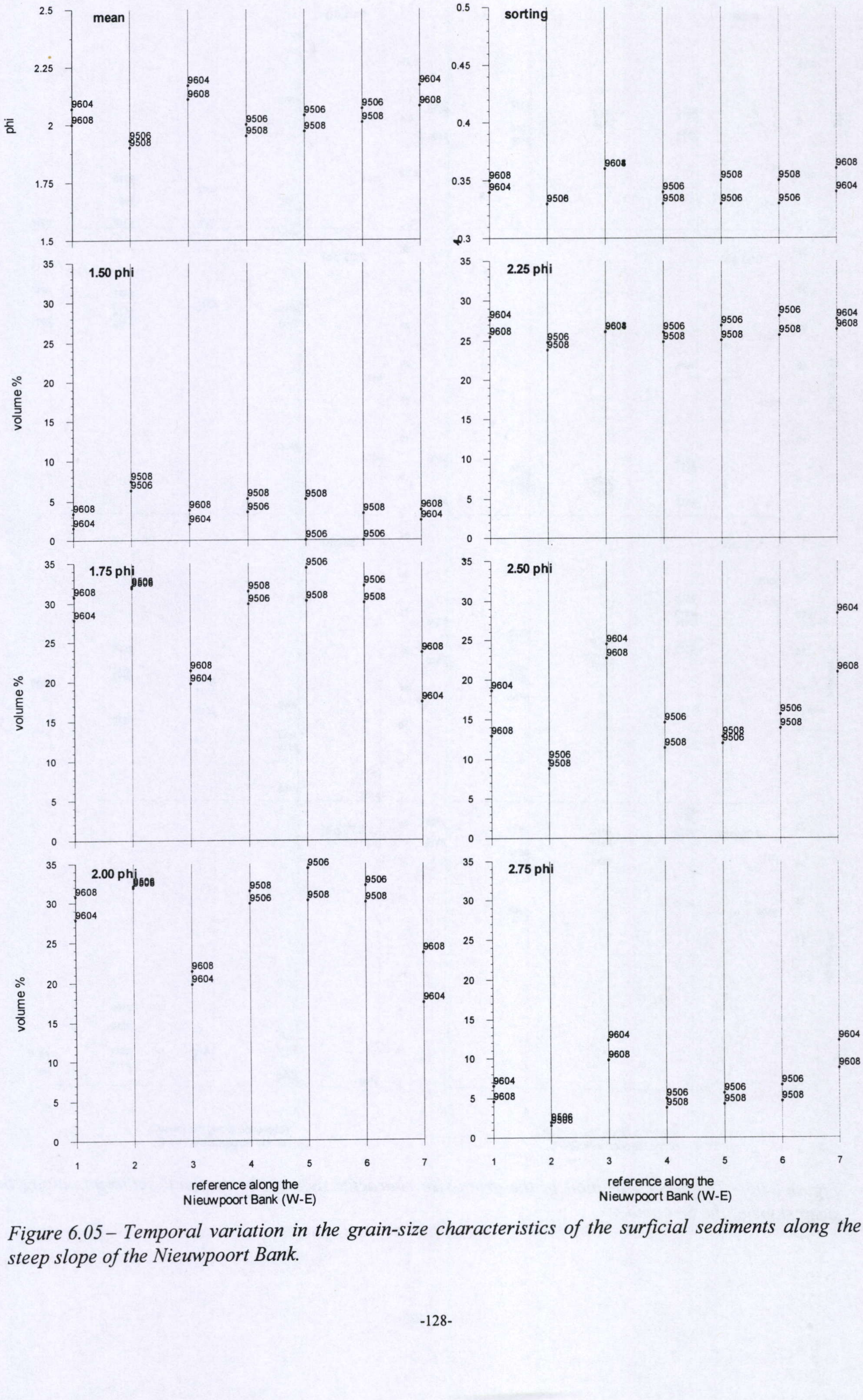


Figure 6.05 – Temporal variation in the grain-size characteristics of the surficial sediments along the steep slope of the Nieuwpoort Bank.

Figure 6.06 – Temporal variation in the grain-size characteristics of the surficial sediments along the steep slope of the Stroombank.

Temporal variation in grain-size characteristics along the Baland Bank

Grab samples characterising the surficial sediments of the Baland Bank were taken on three occasions: February 1996 (11 samples), November 1996 (20 samples) and May 1997 (40 samples). In order to study the temporal variability in grain-size characteristics, the whole of the samples was grouped according to their morphological position within the area. This led to a delineation of 18 characteristic boxes, numbered from north to south (Fig. 6.07). Within the boxes, the distance between the samples is minimal: on average about 100 m with a maximum of 200 m to the north. Figure 6.08 is a visualisation of the temporal variation in grain-size characteristics.

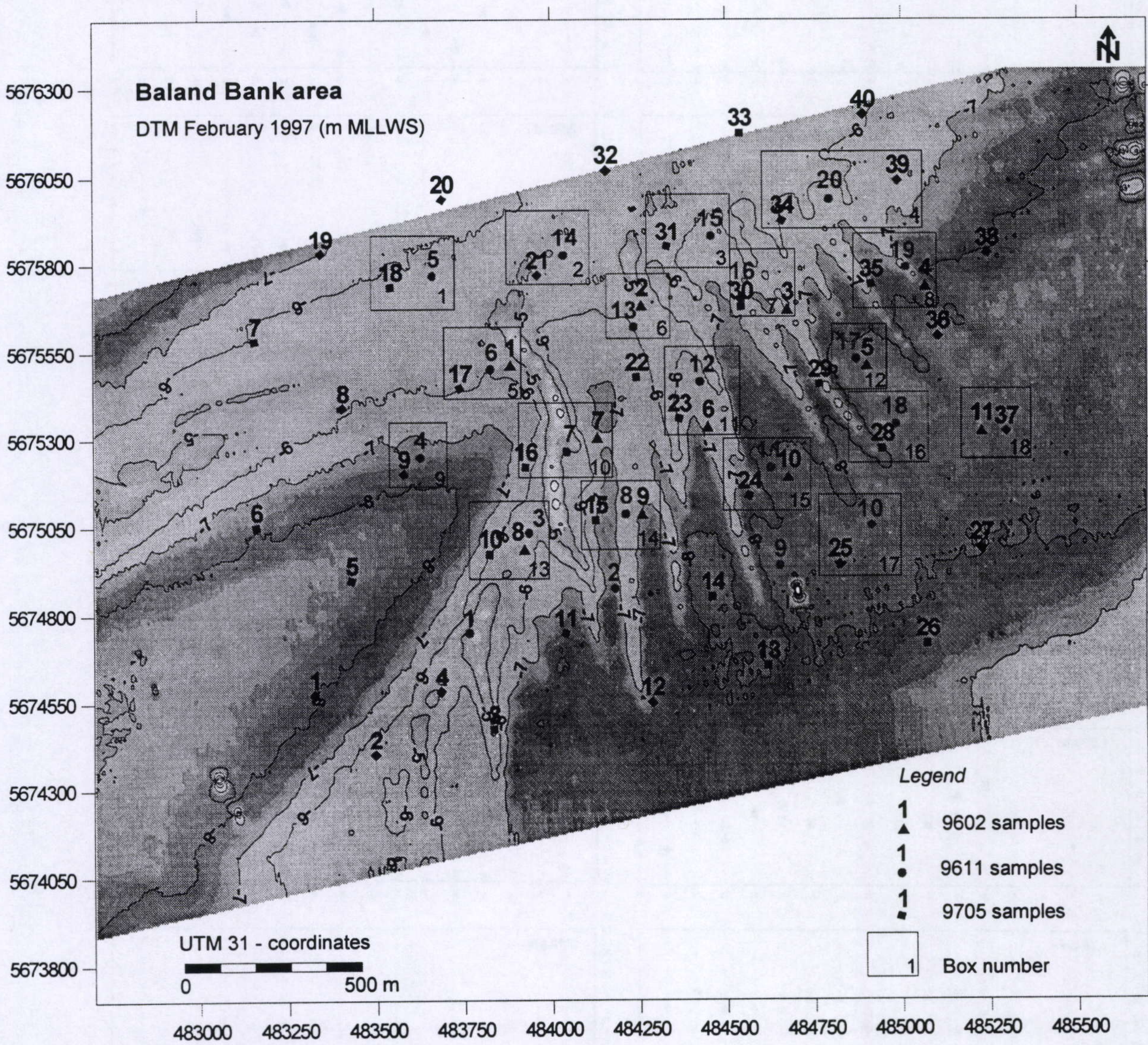


Figure 6.07 – Localisation of the representative boxes for grain-size comparison (grain-size data of February 1996, November 1996 and May 1997).

The upper graphs represent the mean and the sorting of the surficial sediments, whilst the other graphs show the volume percentage variation of each fourth of phi value within the sediments.

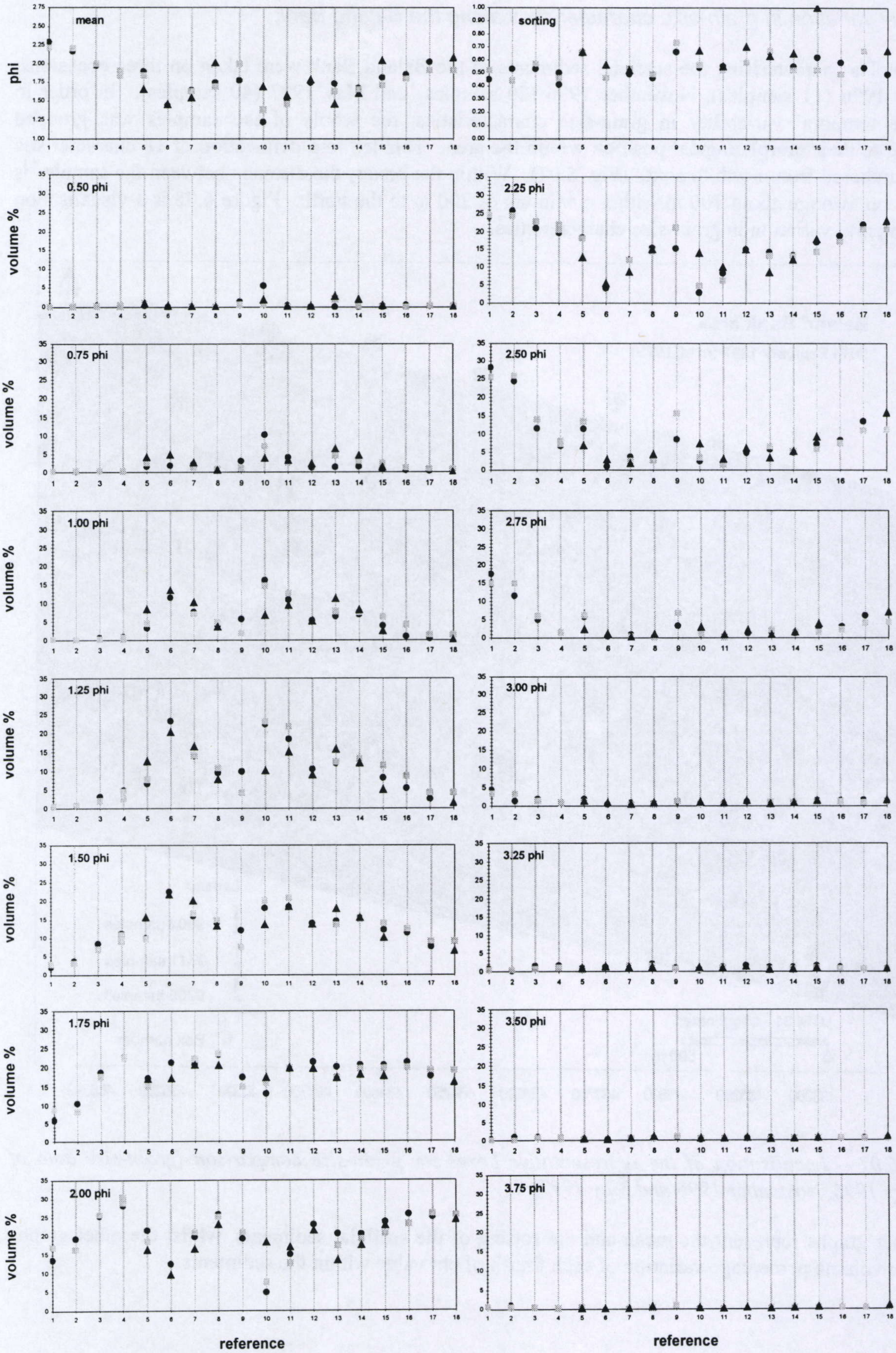


Figure 6.09 - Temporal variation in grain-size along the Baland Bank (grain-size data of February 1996 (triangle), November 1996 (circle) and May 1997 (square)).

Generally, most coherence is found in the samples located to the north of the area. The corresponding sediments are indeed associated with a slightly undulating morphology and are not subjected to the highest shear stresses. The mean and the sorting is similar through time. In the dune area itself, more scatter is found and bias is expected imposed by the grain-size differences between the top and the troughs of the very large dunes. This difference was clarified in Section 5.3.4.3 (Fig. 5.26); from that evidence it can be accepted that a maximum difference of 0.30 ϕ in the mean grain-size and a sorting difference of up to 0.16 ϕ can be due to the morphological position across the dunes. Hence the difference is spatially determined and not temporally.

Comparing the grain-size characteristics through time, it seems that most scatter is found in the boxes 5, 10, 13 and the boxes 8 and 15. The first named boxes are located along the steep slope of the Baland Bank corresponding to a zone where the highest shear stress is expected. Although the distance between the samples may be minimal, a significant shift in grain-size characteristics may be due to a different morphological position. It should be noted that the difference in the sorting is minimal, thus confirming the high hydraulic sorting processes. The scatter in the mean grain-size in the boxes 8 and 15 seems temporally more significant. Though only about 50 m apart, the February 1996 sample is finer than the one of the November 1996 campaign which in turn is finer than the May 1997 one. The sorting of the February 1996 is clearly poorer than the others. The majority of the samples has however no significant temporal fingerprint.

Comparing the three campaigns using the different fractions does not result in a clear trend. Most scatter is found in the 2.00 ϕ (250 µm) interval; the fractions finer than 2.75 ϕ (150 µm) hardly show any differences. Some minor differentiation can be observed for the boxes 12 to 18 (variable). Comparing the November 1996 and May 1997 campaigns, a higher volume percentage of grains between 0.75 and 1.50 ϕ (350 µm) can be observed for the November samples (boxes 15 to 18). From a grain-size of 1.75 ϕ (300 µm), this trend is reversed. Up to the fraction 2.75 ϕ (150 µm), the November 1996 samples have a higher volume percentage.

Summary and conclusions

- the temporal variation of the samples in the Baland Bank area is minimal; this is likely due to the intensity of the hydraulic sorting processes;
- the bias implied by a different morphological position seems to be more important;
- some differentiation can be observed to the south of the dune area: the May 1997 samples have more coarser grains than the November 1996 samples, whilst the latter have a higher volume percentage for the fractions 1.75 to 2.75 ϕ (300 – 150 µm); analogous to the observations along the Nieuwpoort Bank and the Stroombank, this means that the November 1996 samples are representative of higher sediment dynamics: more coarser grains are entrained, and more finer grains are winnowed out and actively transported along the area.

Temporal variation in grain-size characteristics along the southern part of the Middelkerke Bank

Along the southern part of the Middelkerke Bank, surficial grain-size samples have been taken in February 1996 and November 1996. As along the Baland Bank area, the temporal differences are minimal (less than 0.15 ϕ, exceptionally 0.30 ϕ). The November 1996 samples tend to be somewhat finer in texture.

A grain-size trend analysis (GAO & COLLINS (1992)) performed on the mean, sorting and skewness of both data sets resulted in two opposing sediment transport directions (also Section 5.3.4.3) (Fig. 6.09). The analysis on the February 1996 samples resulted in transport vectors merely pointing in a SW to S direction, whilst those of November 1996 pointed dominantly in a W to NW direction.

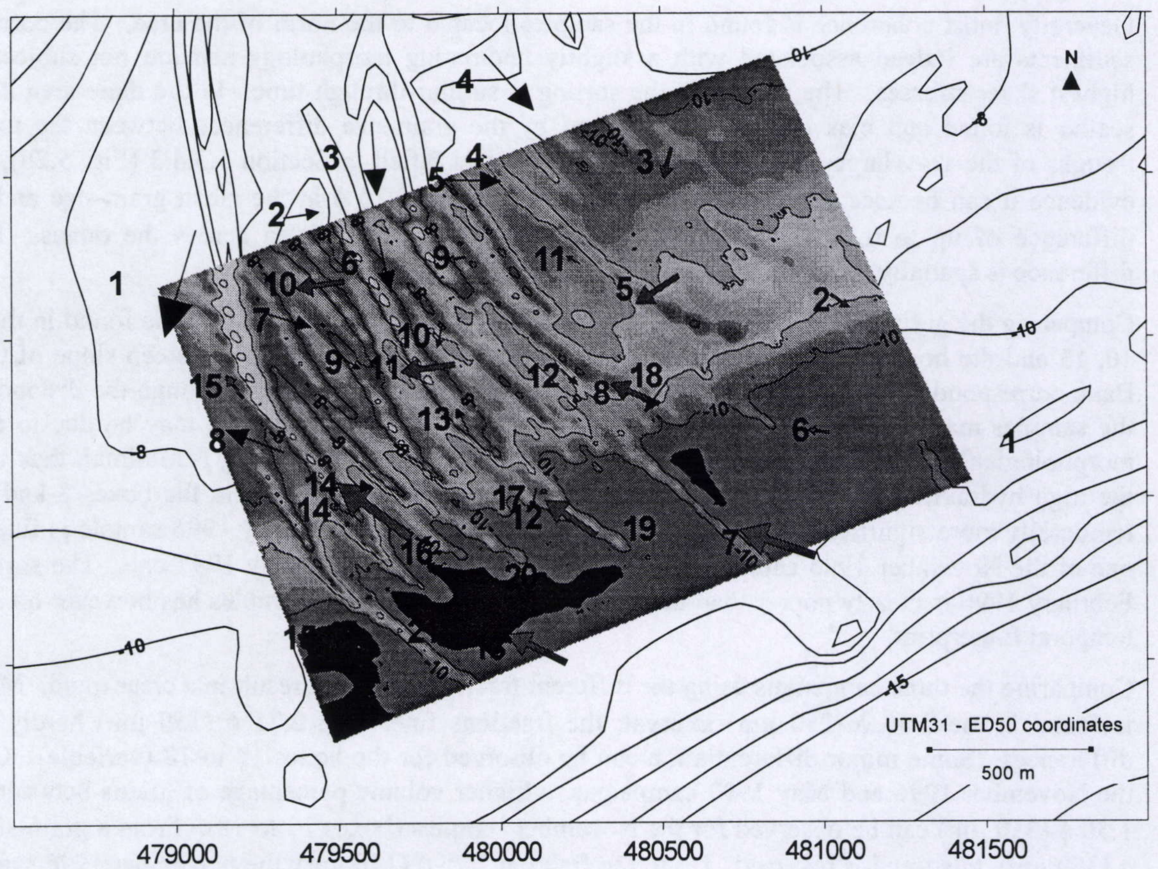


Figure 6.09 - Differences in the areal distribution of grain-size characteristics along the southern part of the Middelkerke Bank (February 1996 (dark, thin arrows), November 1996 (light, thick arrows)).

6.3.2.2. Comparison with observations on the beaches adjacent to the study area

The evidence presented for the temporal grain-size variations along the sandbanks resembles the trends observed along the beach (Figure 6.10). In the period September 1995 till February 1997, the low water line along the coastal stretch Oostduinkerke – Mariakerke has been sampled on a variety of occasions, but in a time period as close as possible to the samplings carried out offshore. The upper 10 cm was preferably sampled as comparative to the sampling depth offshore.

Regardless of the temporal scatter, the spatial variability of grain-size characteristics is confirmed for the 12 sampling campaigns: a coarsening of the surficial sediments in an eastward direction; however no real trend can be observed in the sorting values. Although the beaches west of Nieuwpoort are characterised by a ridge-and-runnel morphology and those east of Nieuwpoort by groynes, no real break in the trends can be observed. However, the variations between the groyneed beaches from Lombardsijde to Mariakerke are likely more significant. It is not clear why the beach of Mariakerke is strongly coarser than the others.

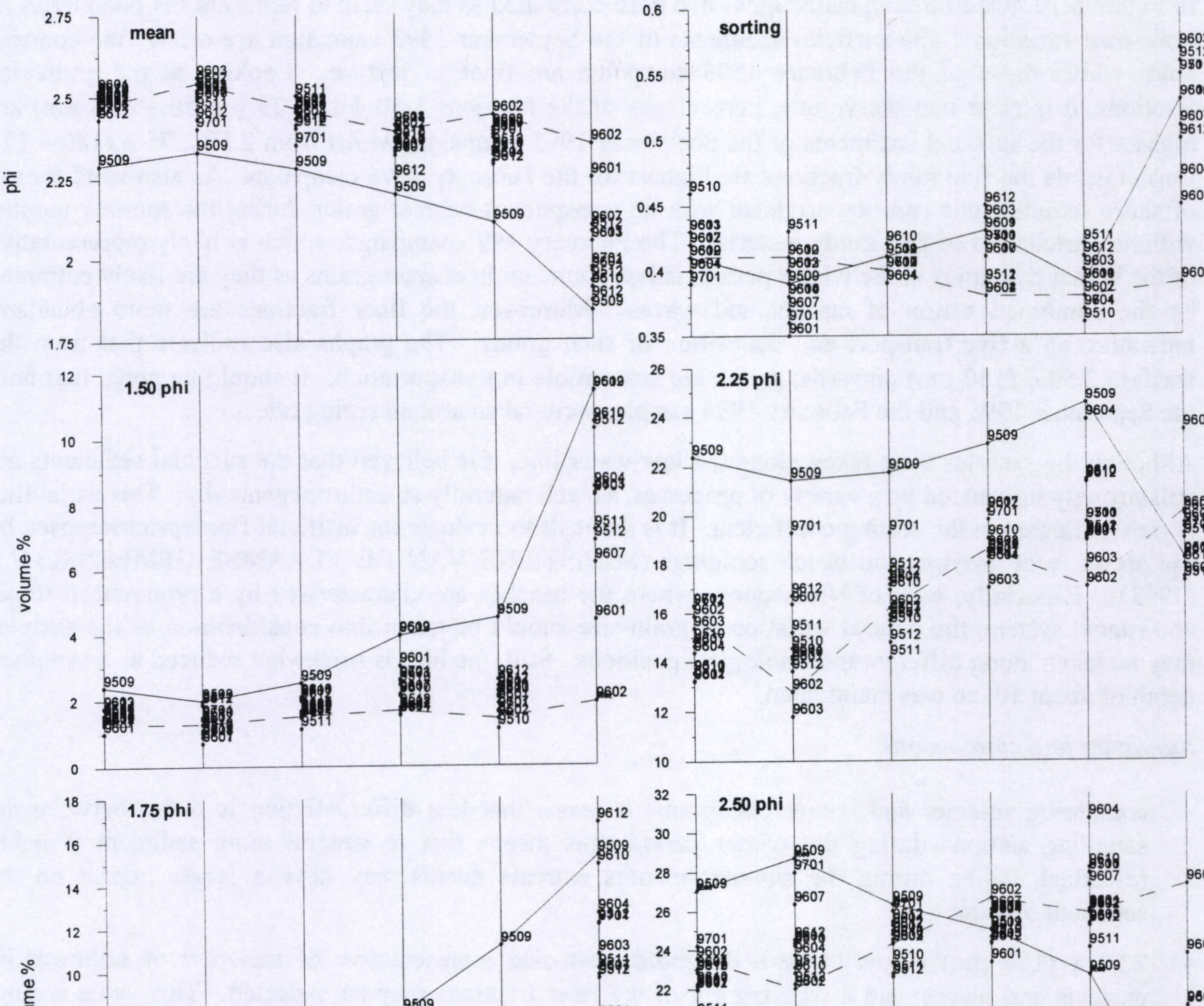


Figure 6.10 – Temporal variation in the grain-size characteristics along the coastal stretch Oostduinkerke – Mariakerke. (Oostduinkerke (6); Nieuwpoort, Groenendijkbad (5); Lombardsijde (4); Westende (3); Raversijde (2); Mariakerke (1) (localisation Fig. 1.01)).

In Figure 6.10, two sampling campaigns have been correlated as they seem to represent the boundaries of grain-size variation. The surficial sediments of the September 1995 campaign are clearly the coarsest ones, whilst those of the February 1996 campaign are finer in texture. Looking at the grain-size fractions, it is clear that the volume percentages of the fractions 1.50 ϕ to 2.25 ϕ (350 – 210 µm) are highest for the surficial sediments of the September 1995 campaign, whilst from 2.50-2.75 ϕ (180 – 150 µm) onwards the fine sandy fractions are highest for the February 1996 campaign. As also valid for the offshore samples, this can be correlated with no transport of coarser grains during the summer months with no enrichment of fine sandy material. The February 1996 campaign, which is likely representative of the higher dynamics in the winter period, is less abundant in coarser grains as they are likely entrained by the combined action of current and waves. Moreover, the finer fractions are more abundant, indicating an active transport and deposition of such grains. The graphs also indicate that from the fraction 2.50 ϕ (180 µm) onwards; grains are susceptible to transportation. It should be noted that both the September 1995 and the February 1996 samples were taken around spring tide.

Although the samples were taken along the low water line, it is believed that the surficial sediments are still strongly influenced by a variety of processes, as well naturally as anthropogenically. This variability is most reflected in the sorting coefficient. It is difficult to evaluate the artificial fingerprint imposed by the presence of groynes and beach scrapings (MINISTERIE VAN DE VLAAMSE GEMEENSCHAP (1993)). Especially, west of Nieuwpoort, where the beaches are characterised by a pronounced ridge-and-runnel system, the natural variation in grain-size should be taken into consideration as the samples may be taken along different morphological positions. Still, the bias is somewhat reduced as a sampling depth of about 10 cm was maintained.

Summary and conclusions

- comparing summer and winter conditions, it seems that less differentiation is found between the sampling stations during the winter period; this means that in general more sediment is being reworked, whilst during the summer months extreme events may have a larger impact on the sediment texture;
- 2.50 ϕ (180 µm) seems to be a threshold grain-size representative of transport of sediment by currents and waves, and a washing out of the finer fractions may be expected. This value is finer than the offshore values: 2.25 ϕ (210 µm) for the Nieuwpoort Bank, 1.75 ϕ (300 µm) for the Stroombank;
- the coarsening trend in grain-size variation to the east may be related to the funnelling effect of the current in the Kleine Rede swale; moreover this swale shallows in an eastern direction implying acceleration effects of the current; hence more coarser grains can be entrained and more finer fractions are being winnowed; the strong decrease in the amount of the finer fractions towards the east may also reflect a difference in availability of sand;
- although no real correlation can be made between the beach sediments and the surficial sediments of the Stroombank, it seems more likely that sediments can be interchanged towards the east;
- the study of grain-size characteristics along beaches is much more complex than offshore due to the variety of processes as well naturally as anthropogenically.

6.3.3. Relation with the hydro-meteorological database

Although the results presented in the previous paragraphs can roughly be explained by seasonal effects, more clarification is needed concerning the specific hydro-meteorological conditions preceding some of the sampling campaigns. Figure 6.11 represents the hydro-meteorological conditions in the intersurvey period of the sampling campaigns; Figure 6.12 details the periods in between the beach samplings.

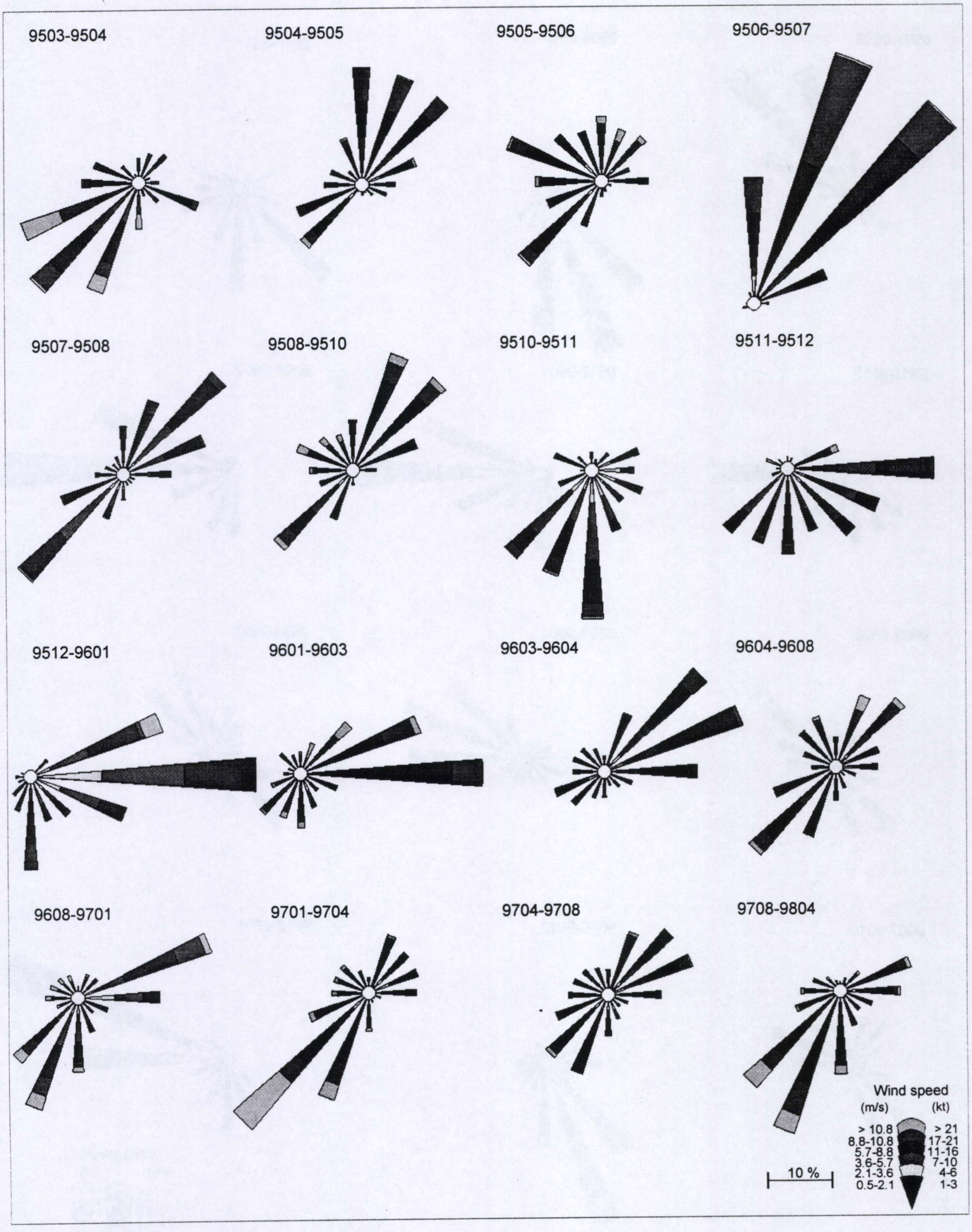


Figure 6.12 – Average wind characteristics for the intersurvey periods of the sampling campaigns (Source data: AWK).

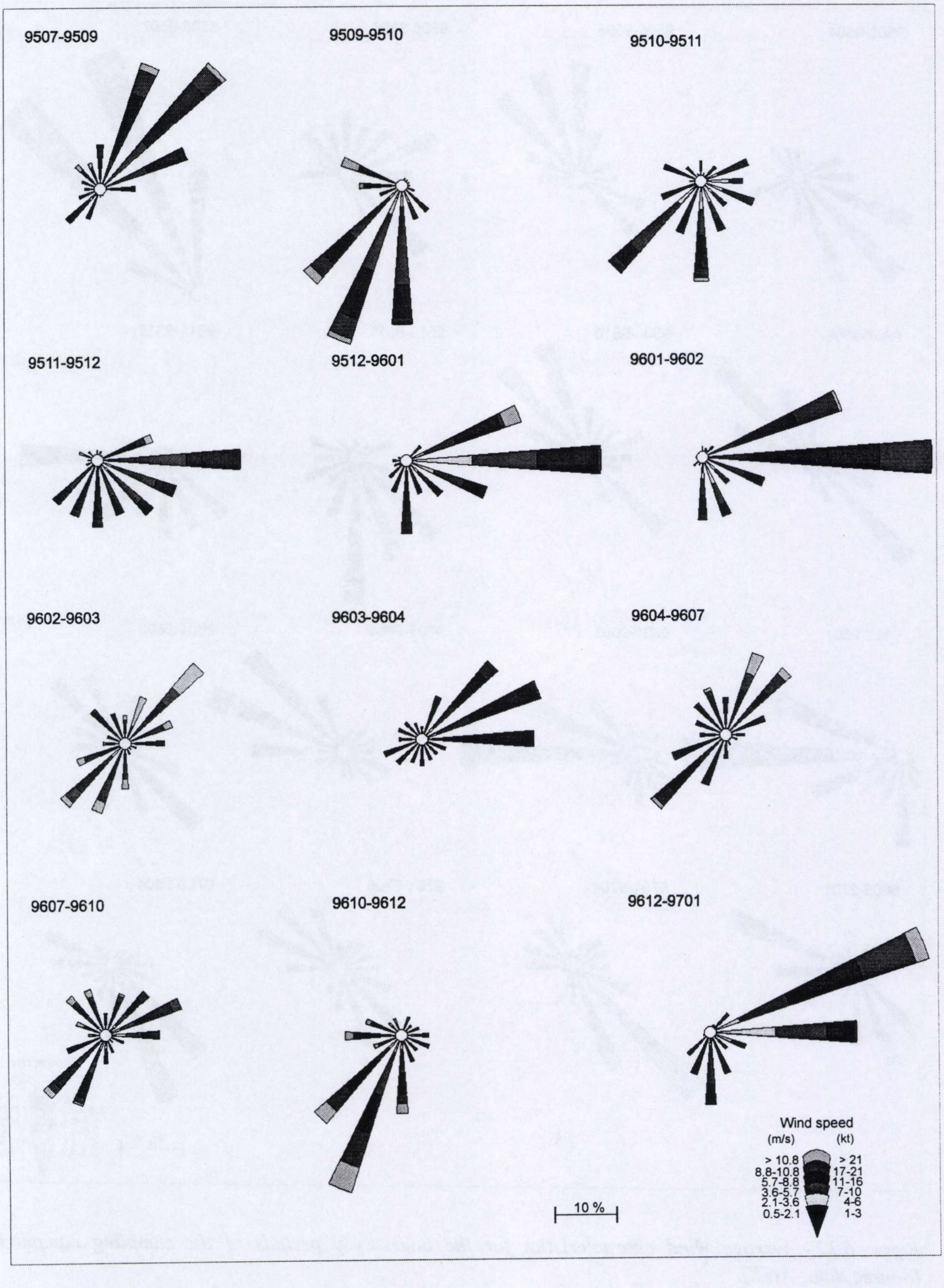


Figure 6.12 – Average wind characteristics for the periods relevant for the beach samplings (Source data: AWK).

Considering the whole of paragraph 6.3.2, it seems most remarkable that the summer situation reflects most diversity in grain-size characteristics. Still as well for the sandbank samples as for those taken along the beach, it was quite remarkable to find the highest abundance of the coarsest grains associated with the summer conditions. This was interpreted as being due to weaker dynamics that are not capable of entraining coarser grains; the lack of finer grains is attributed to the fact that under calmer conditions, no fine sands are actively being transported. However, taking into account the specific hydro-meteorological conditions, those sampling campaigns were preceded by long periods of 4 - 5 Bf NE to NNE winds. Apparently, such winds are not capable to induce an entrainment of sediment; still, the finer sediments seem to be winnowed. From the observed sediment texture, it seems unlikely that an input of sediment is generated from a NE to NNE direction.

Taking into account the hydro-meteorological conditions, the results of the February 1996 beach samples are quite surprising. The observations match the hypothesis that under the rougher winter months more coarser grains are being entrained, whilst also finer grains are actively winnowed out and transported throughout the area. Still, the hydro-meteorological conditions characteristic for that period, were not extremely rough. The autumn of 1995 was characterised by winds blowing from a variety of sectors, from the SW to the NE and only with moderate force. The first two winter months were however strongly indicative of E to ENE winds. These wind directions are aligned with the general configuration of the swales and the coastline. This means that the ebb tidal current may be reinforced. Closer to the coast, the longshore drift can be enhanced, inducing a significant transport of sediment. It is not clear to what extend sediments from the upper beach and at some locations dune sediments, can take part in the transport process.

The grain-size variation along the sampling profile transversal to the Nieuwpoort Bank and the Stroombank confirms the correlation of the temporal differentiation with the seasonally determined dynamics. Remarkable is the coarser texture of the April 1998 samples. The hydro-meteorological conditions corresponded to a period of strong SW winds, meaning that the tidal currents in the swales are reinforced. Hence, more sediment is advected along the swales, but also more coarser grains can be transported. From the hydro-meteorological database, the August 1997 samples are representative of the calmest period. As outlined above, this is reflected in the sediment texture. Generally, it would be suspected that the sediment texture of the July 1995 samples would correspond with fair-weather conditions, though this period was characterised by NE to NNE winds of moderate strength. As outlined above, these wind directions do not align with the direction of the tidal current. Hence, the latter is not significantly reinforced and no active sediment transport takes place. The seabed is likely gradually being swept. The difference between the December 1995 and January 1996 samples is likely due to spring-neap tide effects respectively.

Along the Stroombank, the hydro-meteorological data confirm the lesser dynamic conditions preceding the May 1995 campaign in contrast to the period preceding the October, November and December 1995 campaigns. The samples of the June 1995 and certainly those of the April 1996 campaigns are representative of higher dynamics in contrast to the observations in August 1995.

As mentioned above, the temporal grain-size differentiation along the Baland Bank is merely minimal. This is explained by the intensity of the hydraulic sorting processes. Still, it should be noted that from the hydro-meteorological database, no significant difference in dynamics is expected between the February 1996, November 1996 and May 1997 samples. The November 1996 and the May 1997 campaigns were preceded by periods dominated by rather strong SW winds. The impact of the conditions preceding the February 1996 campaign is somewhat ambiguous. Winds blew predominantly from an E – ENE direction, the latter being stronger. Still, those samples appear to be representative of higher dynamics which is likely attributed to enhanced tidal currents. The results resemble the observations of the beach samples in February 1996.

The trends in grain-size differentiation along the southern part of the Middelkerke Bank is quite remarkable in the sense that the results of both campaigns point in an opposing direction, whilst from the GAO & COLLINS (1992) method a consistent residual transport direction would be expected. The hydro-meteorological conditions before the sampling campaigns corresponded respectively to N – NE winds of less than 6 m/s, and S to SW winds around 6 m/s to more than 10 m/s. Interesting is that the transport directions roughly correspond to the tidal flow alignment at the time of sampling. As the two sampling campaigns were carried out during spring tide conditions, the transport trends likely reflect hydraulic sorting processes. This confirms the sediment transport capacity in the area. It needs emphasis that both campaigns represent rougher conditions, hence finer sediments are likely winnowed out and deposited along the transport pathways (Section 5.4). Spring tide conditions are likely to affect the sediment distribution. The fact that the November 1996 samples are somewhat finer than those of February 1996, corresponds with the observations that the fines are gradually swept by N – NE winds, whilst S to SW winds merely bring in sediments; these are subsequently subjected to the hydraulic regime.

6.3.4. Conclusions

Generally, the differences in grain-size characteristics are seasonally determined. From the observations as well offshore as along the beach, it can be put forward that during the summer months no coarser grains are actively transported; this is reflected in an abundance of such grains in the sediment. Finer grains seem to be depleted; they can be transported by the hydrodynamic agents, but as there is no active transport, those fractions are not renewed. The winter months, representative of rougher conditions, show a reversed trend. Coarser fractions are depleted due to an entrainment by the hydrodynamic forces. Finer grains are actively winnowed out and transported, and are easily replenished. The coarsest grains occur in the swales, the main conductors of sediment. The abundance of coarse grains in the swales is highest during the winter months, meaning that a lot of sediment can be advected.

Although specific hydrodynamical and meteorological conditions may alter the sediment texture, the trends in the variation of grain-size characteristics remain the same; only the volume percentages of each fraction may increase or decrease.

- most deviation from the general trends is observed whenever winds blow consistently from a N to NE direction. More coarser grains are observed; these reflect lag deposits, whilst a strong decrease in the finer fractions is seen. As those wind directions do not align with the tidal currents, no significant sediment transport is induced. Still, the forces may be high enough to wipe the seafloor. ENE to E winds have a different impact. Evidence is presented of the winter period of 1995-1996. Unlike the forces described above, these winds do align with the tidal currents. An enhancement of the ebb peak tidal current is expected; hence sediment can be more actively transported;
- winds blowing from an E to S direction are clearly less frequent and can be characteristic for the autumn period. Due to their sporadic frequency, they likely have a small impact on the seabed sediments;
- S to W winds blow fairly frequent. Southern winds are less important, whilst SSW to WSW winds are the most interesting ones. As those wind directions align with the flood tidal current in the swales, the latter are largely enhanced and induce a significant sediment transport. The swales are the ideal conductors of sediment. A mixture of sediment containing grains coarser than 400 µm, can be brought into the system and made available for further hydraulic sorting;
- although no real evidence can be presented for the impact of winds blowing from the W to N, the strongest winds generally blow from a NW direction and may induce waves having a height of more than 3 m. The associated wavebase likely alters the seabed sediments at depths shallower than - 10 m; hence those winds are associated with erosion, or at least destabilisation.

A difference in grain-size characteristics imposed by the spring – neap tide cycle may explain small-scale variations. The above mentioned wind directions in combination with spring tide conditions can significantly enhance sediment transport.

On the basis of grain-size variations along a cross-shore profile near Katwijk (The Netherlands) before and after a minor storm event, a clear coarsening effect was observed as a result of a winnowing out of the fines (TERWINDT (1962), in: VAN RIJN (1998)). This contrasts to the above mentioned results that merely show a fining trend after rougher conditions. Still, they do not contradict the findings of TERWINDT (1962), but merely imply higher dynamics along the macrotidal Belgian coast. Here, not only finer fractions are winnowed, but they are also actively transported and deposited along the pathway. Moreover, entrainment of coarser grains is observed. The process-based mathematical modelling results on the Katwijk data (coupling of hydrodynamics, sand transport rates and morphology) of VAN RIJN (1998) show an increased bedload transport rate for increasing particle diameters between approximately 100 and 600 µm. During low wave-energy conditions, the median particle diameter along an erosional zone may fine as coarser particles are transported at relatively large rates and hence may coarsen in a depositional zone. During high wave-energy conditions, a coarsening effect is more likely as the finer sediments are carried away. VAN RIJN (1998) also mentions the importance of a hiding factor: hiding of smaller particles, resting or moving between the larger ones.

6.4. Medium-term morphological changes

6.4.1. Introduction

Medium-term morphological changes were studied on the basis of chronosequential bathymetrical surveys along four areas in the coastal zone: the Baland Bank, the interaction zone of the Nieuwpoort Bank and the Stroombank, the southern part of the Middelkerke Bank and the Ravelingen. The term *medium-term* is used, as indicative of the larger response time needed for the morphology to adjust to changes in the hydraulic regime.

The behaviour of the bedforms to the different hydraulic regimes is largely dependant on the bedform sizes involved. Generally, bedforms continuously tend to adjust their size and geometry to the instantaneous flow conditions. It may be accepted that small-scale bedforms respond fairly instantaneously to changes in tidal currents, waves and storm activity, whilst the larger ones may be unaffected due to the long response time involved. It is suspected that the small to medium dunes, having a small storage capacity, may change their orientation during the tidal cycle (JOHNSON et al. (1982)).

Generally, it seems plausible that the duration of the tidal cycle does not allow sufficient time for the entire volume of sediment stored in the larger bedforms (spacing > 10 m) to be reworked entirely. It is thought that the bedform profile is continuously modified by the opposing currents, and that the overall shape represents a state of quasi-equilibrium adjustment to the relative strength of the opposing flows. Still, the question remains how much and how long the threshold is exceeded ?

The equilibrium time is the time needed for the changing flow depth to attain 95 % of its new value. The response time of dunes is function of its volume and the bedload transport rate. The time-span is largest for relatively low bedload transport rates and large changes in volume (WIJBENGA (1990)).

In order to study changes in morphology, two approaches have been followed. As the above mentioned areas are characterised by the presence of large to very large dunes, the changes in the positioning of their crestlines can be an indicator of the ruling dynamics (CASTON & STRIDE (1970)). As the areas were surveyed in detail, contour line maps were processed for each survey and inter-compared. The differences in height can be visualised. Moreover, volume calculations enable to quantify morphological changes.

In the following paragraph, emphasis will be put on the results obtained for the Baland Bank, though examples will be presented from the other areas when needed.

6.4.2. Morphological changes based on the dynamical behaviour of bedforms

The migration history of the very large dunes has been determined based on the accurate positioning of the dune crests in the period 1996 - 1998. To accomplish this, the echosounding data points were visualised in 3D. Subsequently, the shallowest points were determined and also the troughs of the dunes were picked out. A filtering of the selected data points enabled a coupling with the database for further analysis. As the tracklines were closely spaced (50 – 75 m), the shallowest points could be connected to form the crestline of the dunes. The general configuration of the crestlines is supported by the side-scan sonar registrations. It needs emphasis that only the large to very large dunes are taken into consideration. Smaller dunes are too susceptible to changes; hence, it is difficult to evaluate their value as sediment transport indicators (TERWINDT (1971)).

Throughout the study period, a number of cases can be put forward, indicative of the dynamics of the area. The latter will be clarified in Section 6.4.4.

For the subsequent campaigns, the crestlines have been visualised in Figure 6.13. As the December 1995 campaign was merely a reconnaissance survey, only the shallowest points have been indicated. The same holds true for the February 1996 campaign; acquisition errors did not allow to map the position of the crestlines.

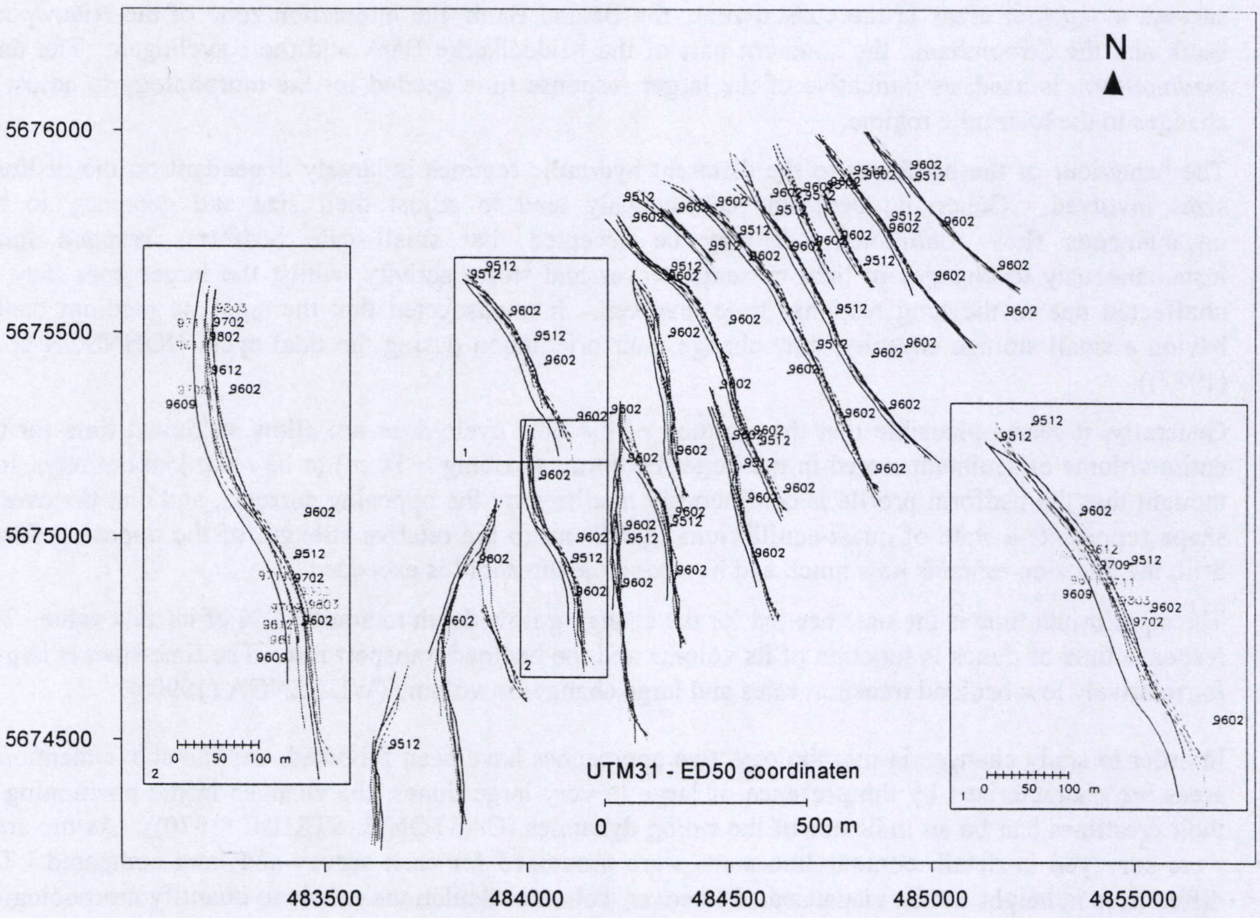


Figure 6.13 – Dune migration history in the Baland Bank area (December 1995, February, September, November and December 1996, February, September and November 1997, February and March 1998).

The September 1996 campaign was quite remarkable as all larger dunes in the Baland Bank area and along the southern part of the Middelkerke Bank showed a reversed asymmetry. This is quite surprising, given the general flood dominance in the area. Figures 6.14 and 6.15 represent the echosounding profiles measured along both areas. Note the difference with Figures 5.04 and 5.06 in Chapter 5. On the side-scan sonar mosaic of the Baland Bank presented in appendix A, the differences in reflectiviness along the dune structures also witness the reversed asymmetry.

As outlined in Chapter 5, the time of surveying in respect to the tidal cycle, is more or less identical for each campaign; this means that the observed changes reflect a difference in dynamics in the period preceding the measurements. Moreover, compared to the other campaigns, the crestline is in its most western position, hence shaped by the ebb tidal current (Fig. 6.14).

In order to evaluate the observations along the Baland Bank made in September 1996, comparative bedform evidence was sought in the preceding campaigns. Although the December 1995 had a more global character, some dunes were detected having dune heights of more than 1 m. The position of the dune crests was located more to the east (ranging between 58 m along the sandbank and 28 m along the easternmost dunes). During the February 1996 campaign, 7 tracklines were sailed along the Baland Bank dune area. As expected from the December 1995 campaign, large to very large dunes were detected east of the small sandbank. Their heights even attained values around 2 m. The exact location of the crest was however difficult to determine as acquisition problems prevented a normal recording of the DGPS signal. The position of the crestlines of the February 1996 dunes should thus be considered qualitatively. Compared to the September 1996 dunes, the crests merely represented a flood dominance. Moreover, the positions of the February 1996 campaign align more or less with those measured during the December 1995 campaign. Storminess during the May 1996 campaign prevented any verification.

The November 1996 campaign clearly witnesses the impact of the dominant flood current. The position of the crestlines shifted on average 10 m in a northeastern direction, with a maximum of 20 m along the central axis of the area. All large dunes had an asymmetry pointing in the direction of the flood dominant current. Towards the north and the south, where the large dunes fade out in the Grote Rede swale, the changes are reduced to less than 8 m.

The crestline positions derived from the December 1996 measurements only fluctuated about 5 m around the November 1996 positions. Given the DGPS positioning error and bias associated with the methodology used, it seems likely that the crestline remained more or less stable. The asymmetries of the dunes were flood-dominated.

The February 1997 campaign revealed flood-dominated large to very large dunes. Their crestline only showed a minor adjustment to the ruling hydraulic regime. The positions of the dune crests remained fairly stable, except for some shifts of up to 15 m where the dune crest showed a bending in the flood direction.

Some fluctuations are observed of the crestline of the September 1997 dunes in respect to those of February. The crestline of the sandbank shifted around 8 to 10 m in a westwards direction, though no real variations are observed for the dunes lying more to the east.

Generally, the dune crests of November 1997 fluctuated around those of September. Along the sandbank, as well westward as eastward displacements are observed.

No real changes are observed comparing the positions of the February 1998 and November 1997 crestlines.

However, the March 1998 crestlines significantly shifted in an eastwards direction. Along the sandbank a shift of 8 to 10 m is observed. Surprisingly, also the easternmost dunes even showed a variation of 10 to 15 m. Towards the Grote Rede swale, the differentiation became minimal.

Figure 6.16 represents the morphological variation between the campaigns September 1996 and March 1998. In this period, the crestline of the sandbank shifted 20 to 38 m towards the northeast. In the dune field, an average shift of 20 m is observed. The values are lowest towards the Grote Rede swale.

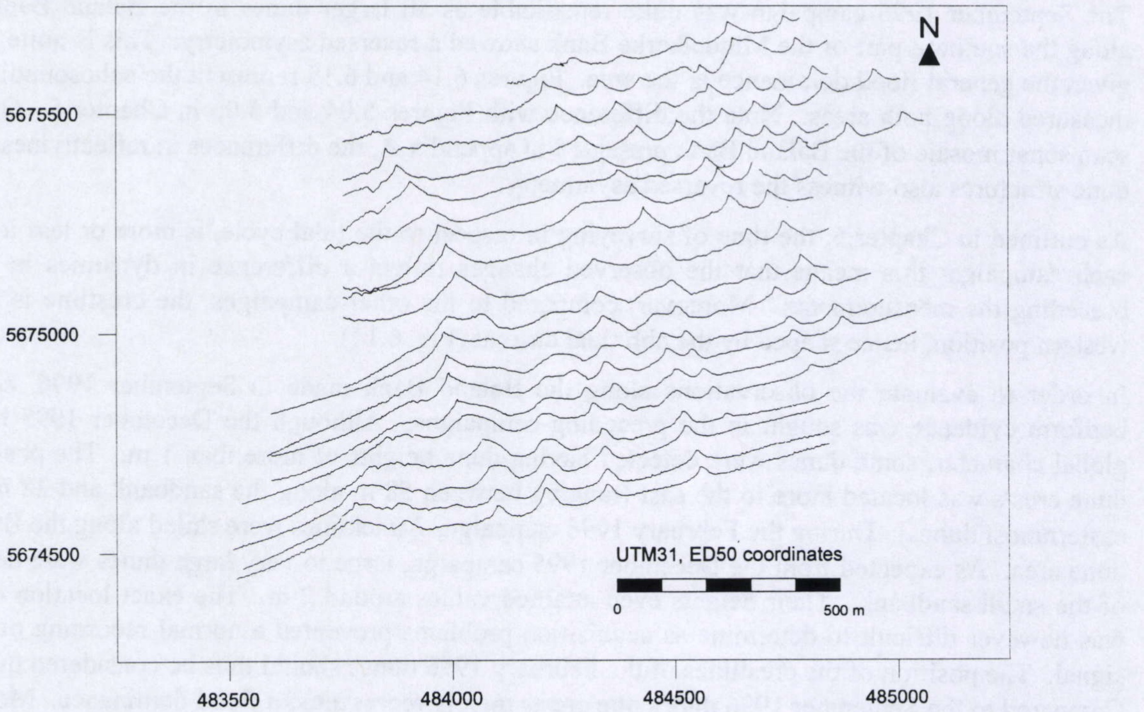


Figure 6.14 – Baland Bank. Spatial diagram of the echosounding profiles (September 1996).

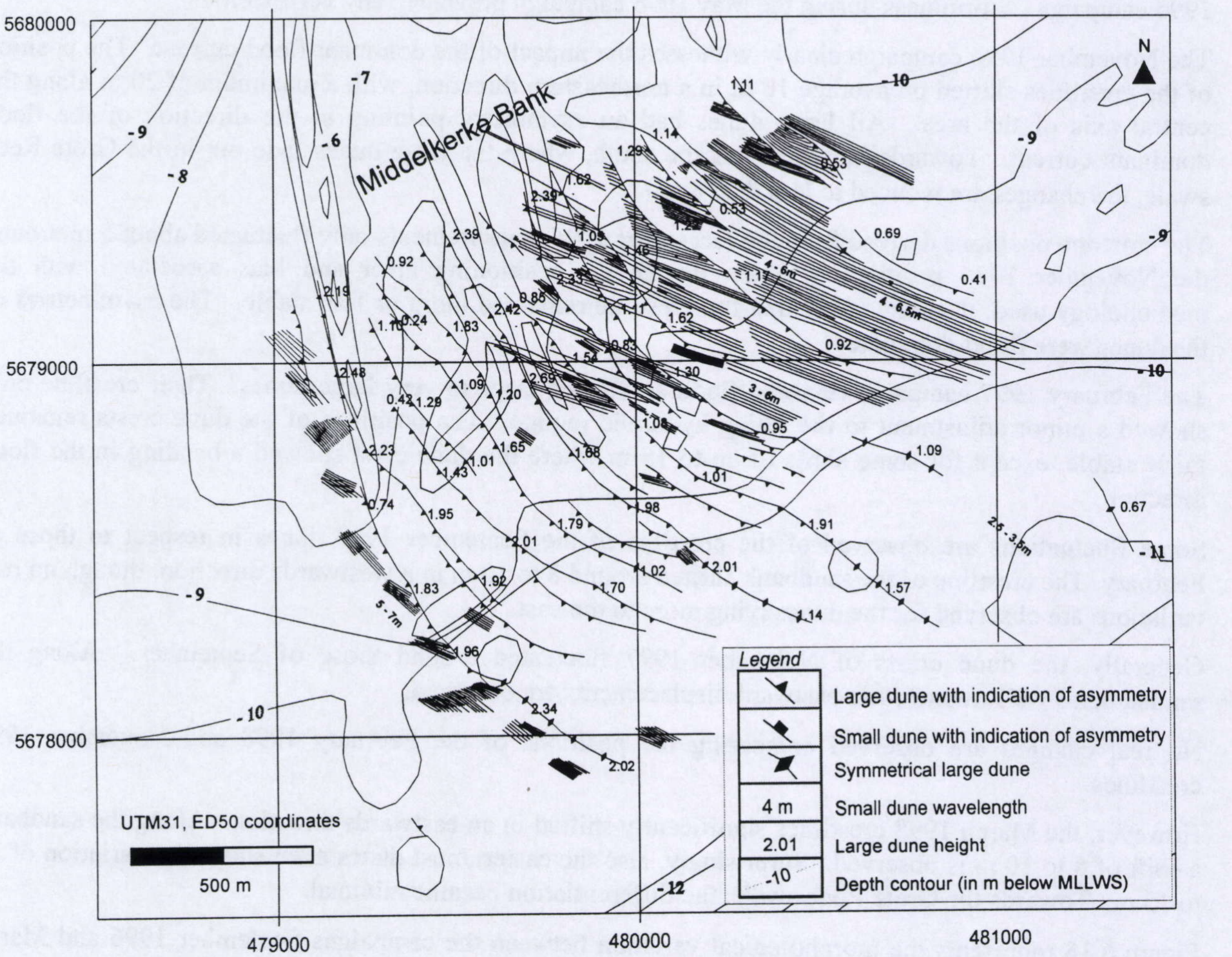


Figure 6.15 – Southern part of the Middelkerke Bank. The areal distribution pattern of the crestlines of the large to very large dunes and their superimposed small to medium dunes (September 1996) (O'SULLIVAN 1997).

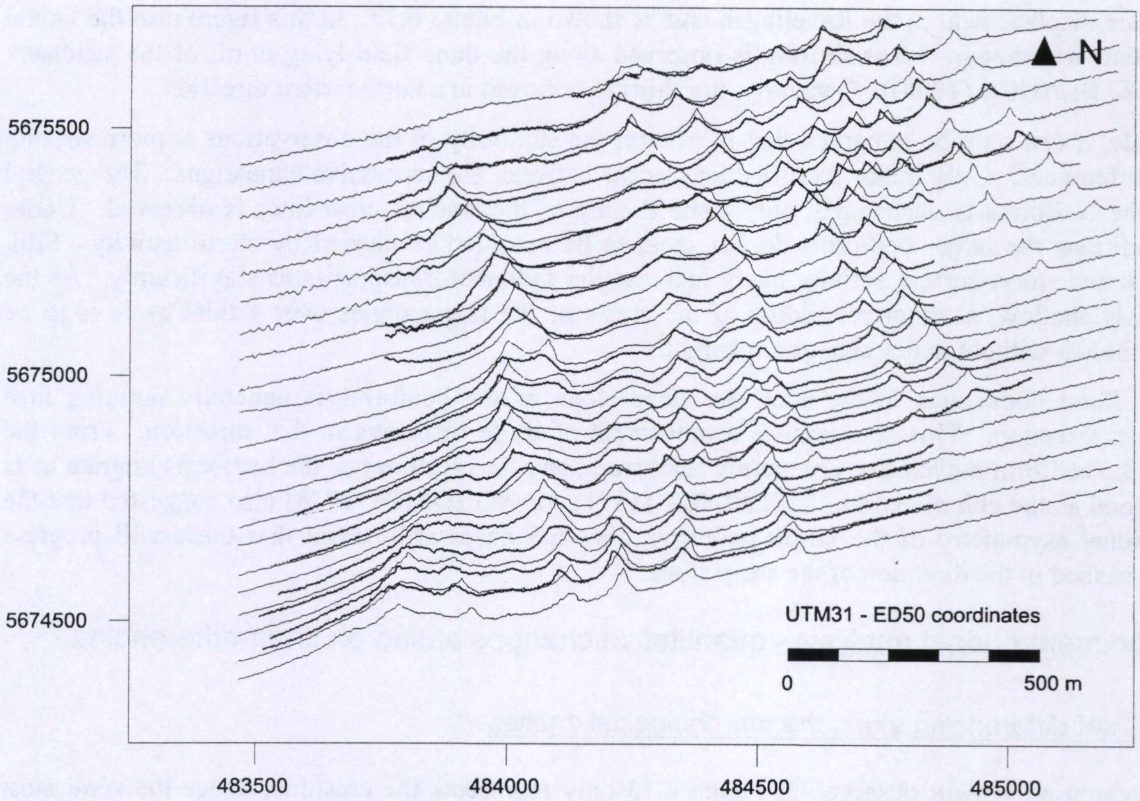


Figure 6.16 – Baland Bank. The morphological variation between the campaigns September 1996 (thick line) and March 1998.

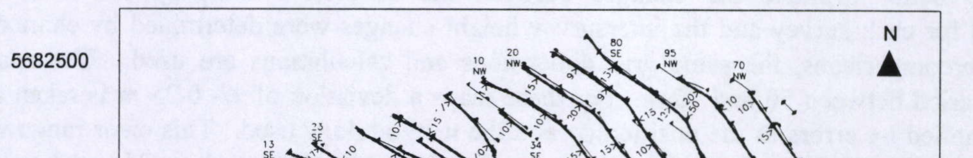


Figure 6.17 – Ravelingen. The crest net displacement between September 1997 (thick line) and March 1998 (DELGADO BLANCO (1998)).

The crest net displacement in the Ravelingen area is shown in Figure 6.17. In this figure also the lateral displacements are shown. Most shifting is observed along the dune field lying north of the sandbank (DELGADO BLANCO (1998)). Generally, the shifting occurred in a northeastern direction.

To conclude, it can only be remarked that in general the similarity of the observations is more striking than the differences. Only minor modifications occur between the successive campaigns. The general shape of the bedforms is unchanged; only some flexing of the sinuous crest lines is observed. Under rough conditions the larger bedforms do not seem to be moulded or blurred by storm activity. Still, storm-wave and storm-current activity likely increase the sediment transport rates significantly. As the area is fairly shallow, a minor rebuilding of the crests of the larger dunes over a tidal cycle is to be expected, though without major changes in height.

Given the flood dominance in the area, the steep slope of the bedforms is generally pointing in a northeastern direction. This also implies a movement of those bedforms in that direction. From the evidence, the bedform movements are merely fluctuating and the crestlines of the bedforms migrate in as well the flood as the ebb direction. TERWINDT (1971), LANGHORNE (1973) also suggested that the cross-sectional asymmetry of the larger bedforms does not necessarily mean that these will progress across the seabed in the direction of the steep slope.

6.4.3. Sediment budget analysis - quantitative changes based on chart differencing

6.4.3.1. Chart differencing along the morphological entities

The differential movement observed in Figure 6.13 only represents the crestline, hence the zone most vulnerable to changes. This implies that these changes may merely reflect short-period reversals in net sediment transport without taking into account the global behaviour of the bedforms.

In order to better evaluate the changes between the successive campaigns, contour maps were interpolated for each survey and the intersurvey height changes were determined by chart differencing. For the intercomparisons, the same grid dimensions and calculations are used. The spacing of the tracklines varied between 50 and 75 m. For these maps a deviation of +/- 0.25 m is taken as the likely variation implied by errors in the positioning and the methodology used. This error range was justified by determining the difference between the measured and calculated xyz-values (November 1997). From this, only 0.2 % of the values showed an error that exceeded the limit of +/- 0.25 m. If an error limit of +/- 0.10 m is taken, an exceedance of 2.6 % is found.

The chart differencing operations have been performed on the data sets of the Baland Bank area (Fig. 6.18, 6.19), the southern part of the Middelkerke Bank (Fig. 6.20), the Ravelingen (Fig. 6.21) and the Westdiep swale (Fig. 6.22).

As was expected from the previous paragraph, remarkable changes could be observed between the November and September 1996 campaigns (Fig. 6.18). A general accretional trend is determined with height differences of up to 1 m. Still, the crestal zone lies within the stability margin. Most accretion is seen in the Westdiep swale, and in the troughs and gentle slopes of the large to very large dunes.

A reversed trend is seen, comparing the December and November 1996 campaigns. The area was generally stable, meaning that the bulk of the sediments deposited before, remained relatively undisturbed. Only, some erosional spots are seen along the crestal zones and along the sandbank itself.

Comparing the February 1997 and December 1996 depth values, another remarkable situation is found. Although the area generally witnesses accretion, this trend is mainly observed to the north of the area. Moreover, the crestal zone of the bedforms has also accreted. The swales Westdiep and the Grote Rede show no significant depth changes.

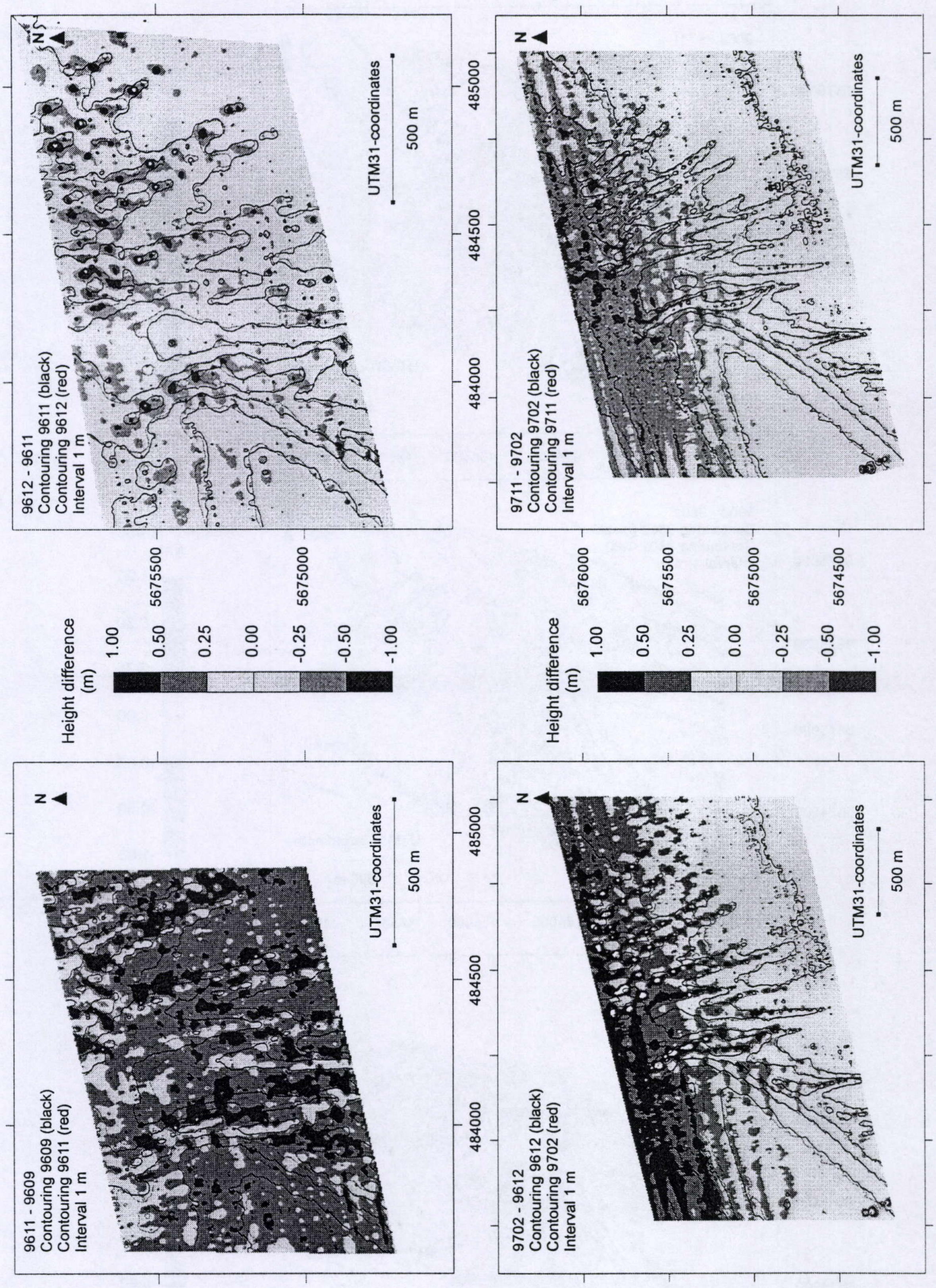


Figure 6.18 – Baland Bank dune area. Chart differencing November – September 1996. December – November 1996, February 1997 – December 1996, November – February 1997.

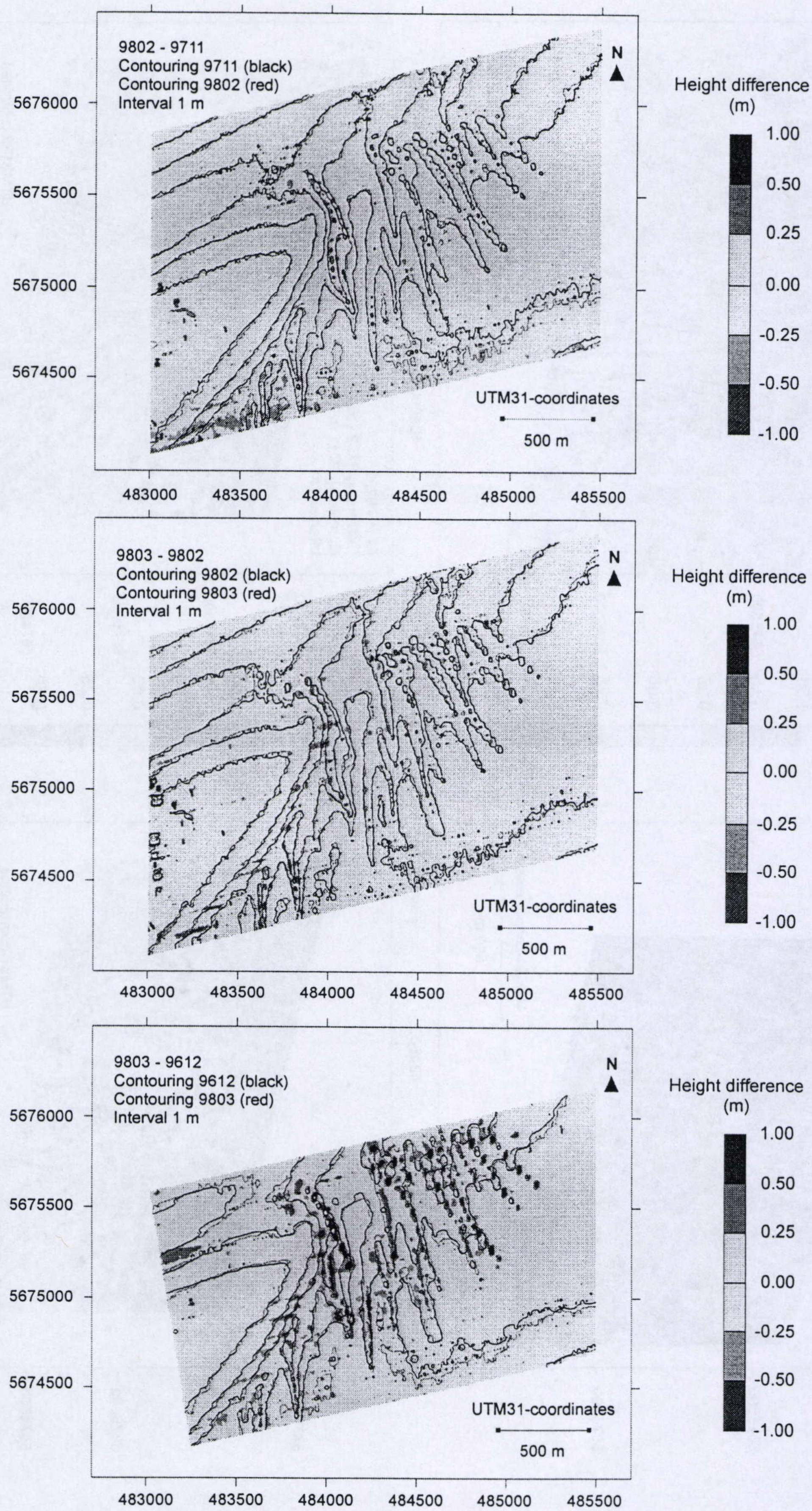


Figure 6.19 – Baland Bank dune area. Chart differencing February 1998 – November 1997; March – February 1998 and March 1998 – December 1996.

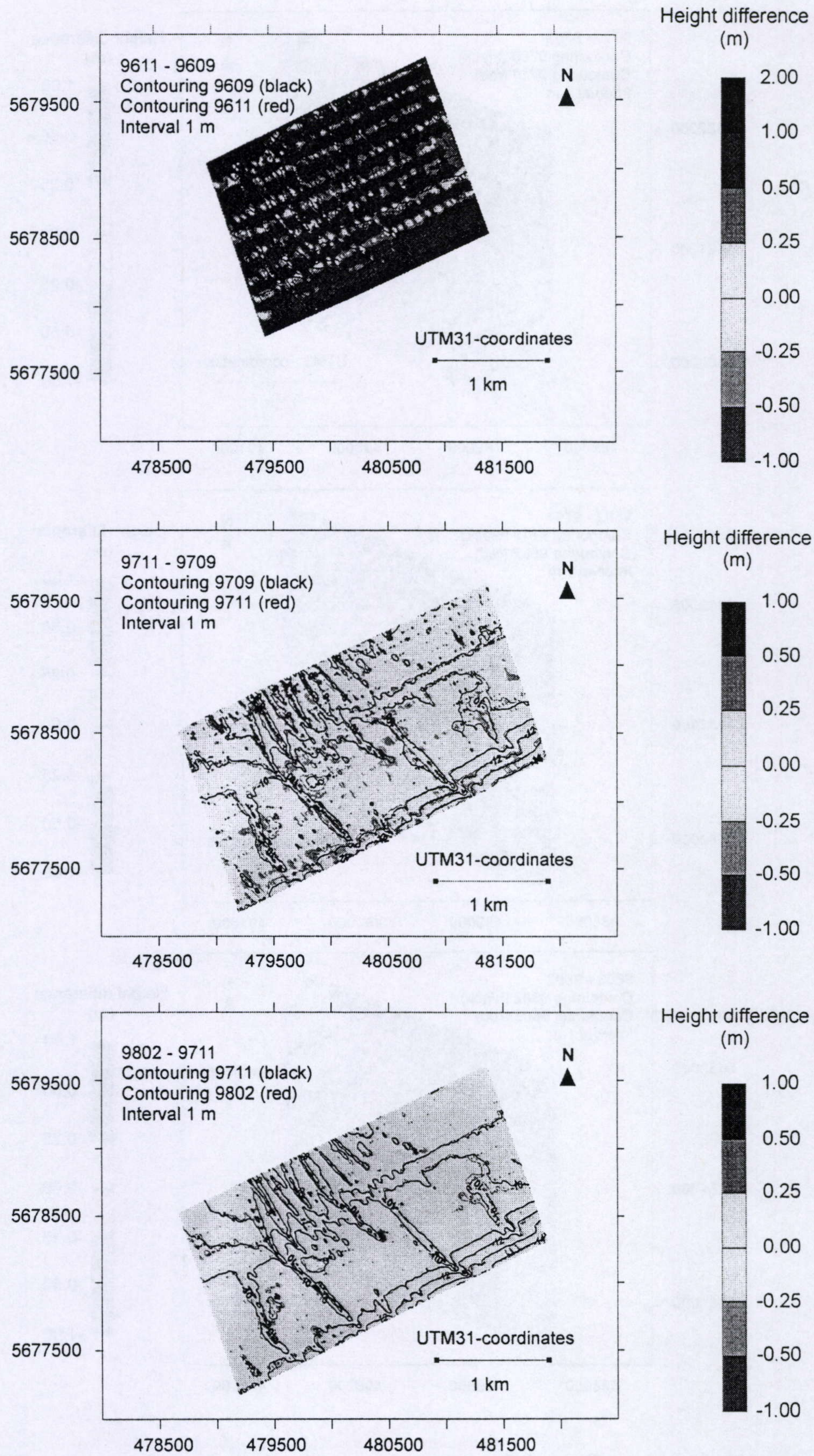


Figure 6.20 – Southern part of the Middelkerke Bank. Chart differencing between the campaigns November - September 1996, November - September 1997 and February 1998 - November 1997.

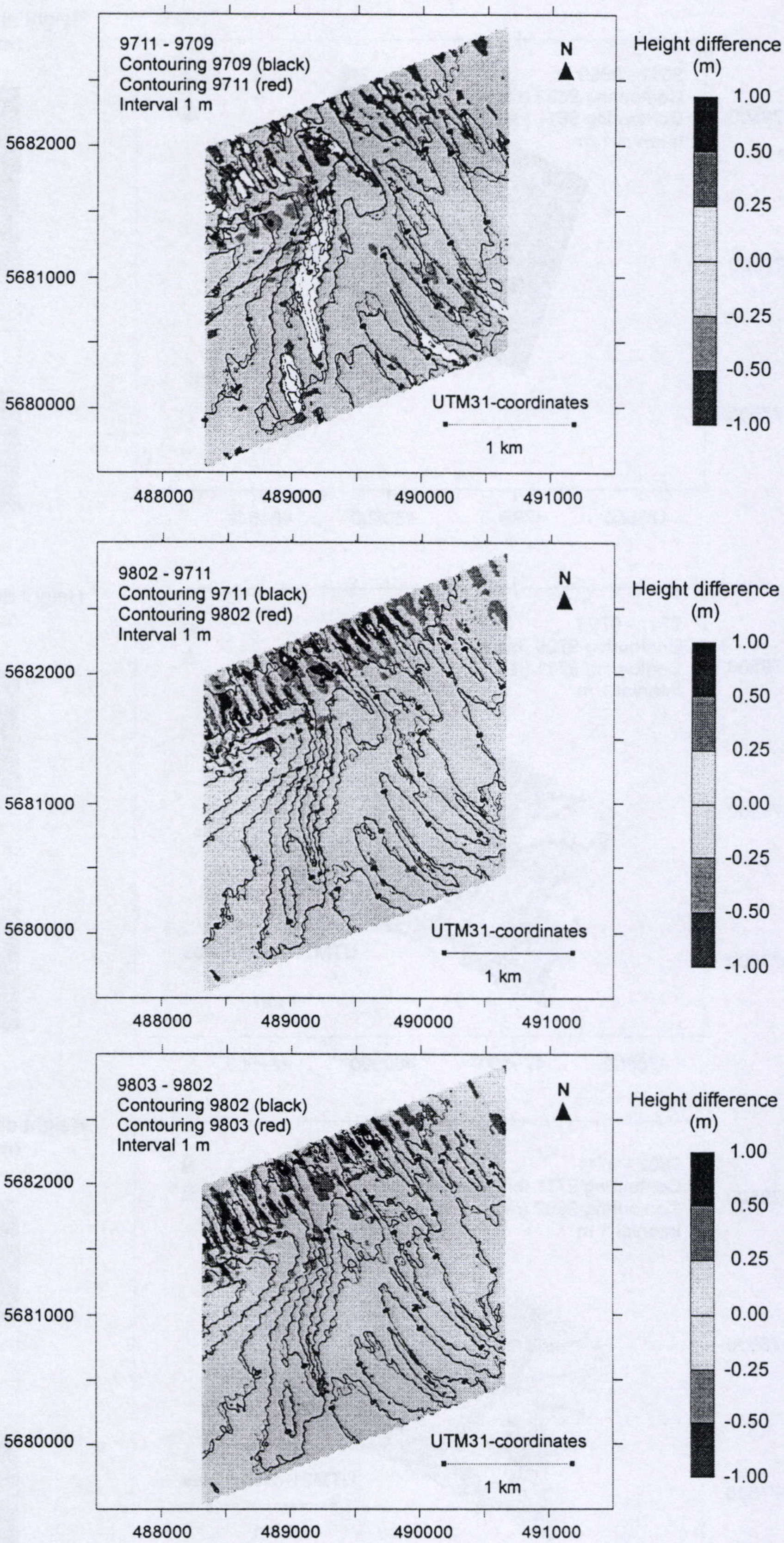


Figure 6.21 – Ravelingen. Chart differencing between the campaigns November – September 1997, February 1998 - November 1997 and March – February 1998.

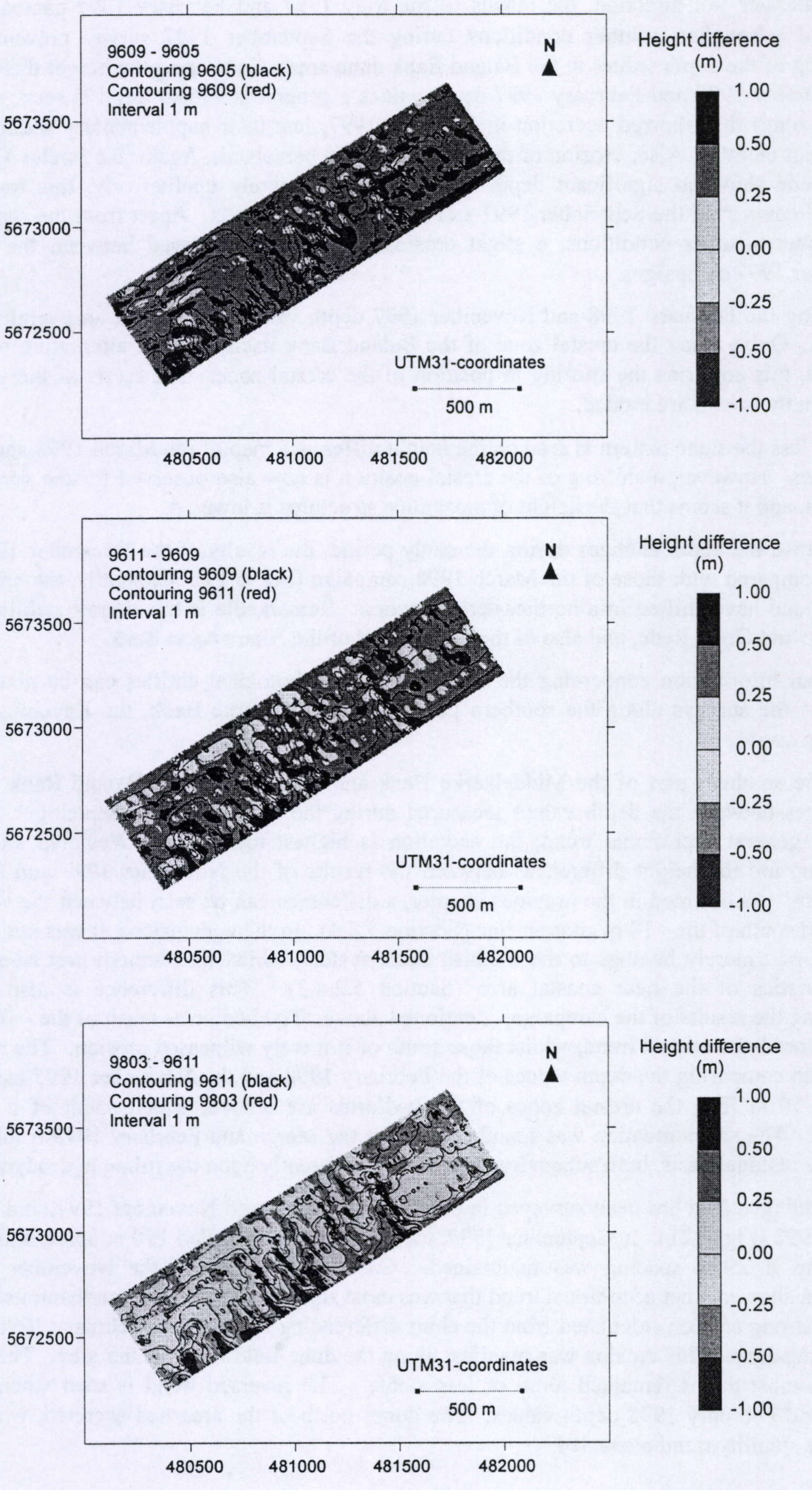


Figure 6.22 – Westdiep swale. Chart differencing between the results of the campaigns September – May 1996, November – September 1996 and March 1998 – November 1996.

Due to another sail direction, the results of the May 1997 and February 1997 campaigns can not be compared. Rougher weather conditions during the September 1997 survey prevented an accurate measuring of the depth values in the Baland Bank dune area. Comparing the height differences between the November 1997 and February 1997 depth values a general erosional trend is seen. It is remarkable that the zones that showed accretion in February 1997, lost their supplementary sediments during the subsequent months. Also, erosion of the crestal zones is perceived. Again, the swales Westdiep and the Grote Rede show no significant depth changes though, merely qualitatively, this trend was already observed comparing the September 1997 and February 1997 results. Apart from the scatter imposed by the rougher weather conditions, a slight erosional trend was observed between the September and November 1997 campaigns.

Comparing the February 1998 and November 1997 depth values (Fig. 6.19), an overall stability can be deduced. Only, along the crestal zone of the Baland Bank itself, erosion alternating with accretion is observed; this confirms the shifting in position of the crestal zone. The crests of the very large dunes located in the south, are eroded.

More or less the same pattern is seen on the height difference map of the March 1998 and February 1998 campaigns. However, a shifting of the crestal position is now also observed for the very large dunes to the south, and it seems that the height of most dune structures is lowered.

To visualise the depth changes during the study period, the results of the December 1996 campaign is finally compared with those of the March 1998 campaign (Fig. 6.19). Generally, the crestal zones have accreted and have shifted in a northeastern direction. Remarkable is the overall stability of the swales Westdiep and Grote Rede, and also of the eastern part of the Nieuwpoort Bank.

Additional information concerning the evolution of morphological entities can be given based on the results of the surveys along the southern part of the Middelkerke Bank, the Ravelingen area and the Westdiep swale.

Along the southern part of the Middelkerke Bank and analogous to the Baland Bank area, the height differences between the depth values measured during the November and September 1996 campaigns reveal a general accretional trend; the accretion is highest towards the Westdiep swale (Fig. 6.20). Interesting are the height differences between the results of the November 1997 and September 1997 campaigns. As outlined in the previous chapter, a difference can be seen between the very large dunes, north and south of the - 10 m contour line (Section 5.2.4). In the conclusions, it was put forward that the northern part merely belongs to the Flemish Bank system, whilst its southern part resembles more the characteristics of the near coastal area (Section 5.2.4.3). This difference is also apparent when comparing the results of the campaigns mentioned above. The bedforms north of the - 10 m line showed a pronounced accretional trend, whilst those south of it merely witnessed erosion. The reversed trend is seen when comparing the depth values of the February 1998 and the November 1997 campaigns. North of the - 10 m line, the crestal zones of the bedforms are eroded, whilst south of it some accretion occurred. The same situation was found comparing the March and February 1998 results. This means that, on a residual basis, both subenvironments react differently upon the ruling hydrodynamical forces.

The Ravelingen area has been surveyed in detail in September and November 1997, and in February and March 1998 (Fig. 6.21). In September 1997, the tracklines were sailed 150 m apart, whilst for the other campaigns a 75 m spacing was maintained. Chart differencing of the November and September campaign showed a net accretional trend that was most significant along the sandbank itself. Remarkable was the strong erosion calculated from the chart differencing between the February 1998 and November 1997 campaigns. This erosion was manifest along the dune field north of the area. The swales and the southern most dunes remained more or less stable. The reversed trend is seen when comparing the March and February 1998 depth values. The dunes north of the area had accreted, whilst towards the south the stability trend overruled.

Although only a few lines were repetitively sailed in the Westdiep swale, the results are still interesting as they may give information concerning the provenance of the sediments. Moreover, due to rough weather conditions, the Westdiep swale was the only subenvironment that could be surveyed during the May 1996 campaign. Comparing the depth values of this survey with those of September 1996 reveals an overall accretional pattern (Fig. 6.22). The bedforms did however not shift in position. As shown for the Baland Bank and the southern part of the Middelkerke Bank, also the Westdiep swale showed a general accretion trend when comparing the results of the November and September 1996 campaigns. However, the crestal zone of the bedforms tend to be stable. A dominance of an erosional pattern is observed if the depth values of the March 1998 and November 1996 surveys are compared. Although this trend is valid over a period of 16 months, it is remarkable that the seafloor of the swale is fairly stable, whilst the bedforms have shifted in a northeastern direction.

6.4.3.2. Volume variations

In order to quantify the changes observed between the successive campaigns, a common area was extracted from each subenvironment and the corresponding volumes were calculated.

As all the subenvironments (i.e. the Baland Bank, the southern part of the Middelkerke Bank, the Ravelingen and the Westdiep swale), were measured in March 1998, this campaign was chosen as reference survey. Thus, the graphs in Figure 6.23 and 6.24 represent the relative volume differences of each campaign compared to the volume calculated for the March 1998 campaign. The values represent the volume of sediment between specific bathymetric levels. Rough weather conditions during the February 1997 campaign only allowed a limited survey along the southern part of the Middelkerke Bank; hence two extracts were made of this area. All surveys are compared based on volume differences for the smallest extract, whilst a larger area can be compared for the campaigns September, November 1997 and February, March 1998.

Comparing the relative volume differences of the 4 subenvironments, more or less the same trends can be found. As could be expected, most scatter is found for the shallowest regions. The latter represent the smallest areas; thus bias is also imposed by randomness. Moreover, these areas are also most susceptible to changes. Interesting however, is the depth at which the volume differences reduce to zero. For the small sandbank areas, - 9 to - 10 m seems to be the average depth of disturbance, whilst for the southern part of the Middelkerke Bank, changes can be expected up to a level of - 11 to - 12 m. In the Westdiep swale - 10 to -11 m seems to be the limit.

Temporally, the volume changes are most interesting for the Baland Bank area. The September 1996 campaign is clearly lowest in volume. As could be expected from the chart differencing, the volume increased significantly afterwards; this is witnessed by the volumes representative of the November campaign. The results of December 1996 showed a decrease in volume which was most severe for the shallow regions. Deeper than - 8 m, the volumes seem to be stable. As also apparent from the chart differencing, an important increase in volume was observed between the December 1996 and February 1997 campaigns. It should be noted that the extra amount of sediment was partly deposited on top of the sediments that originated from a period in between September and November 1996. These were hardly eroded afterwards. Remarkable is the strong decrease in sediment volume represented by the September 1997 results. It is however interesting that the trend resembles the results of the September 1996 campaign. The November 1997 volumes were again much higher, whilst afterwards they decreased again as is shown for the February and March 1998 campaigns.

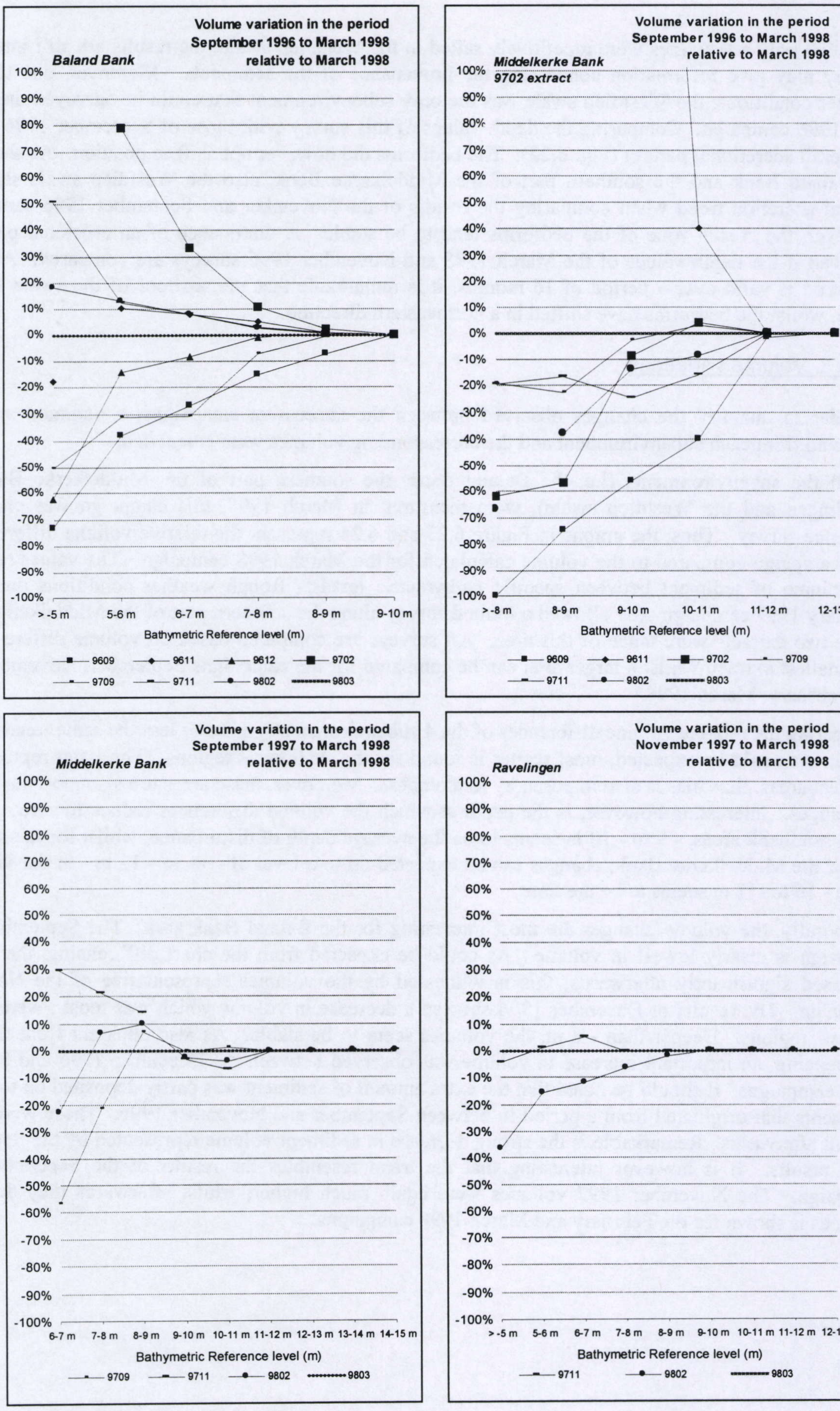


Figure 6.23 – Relative volume variations in the sandbank areas.

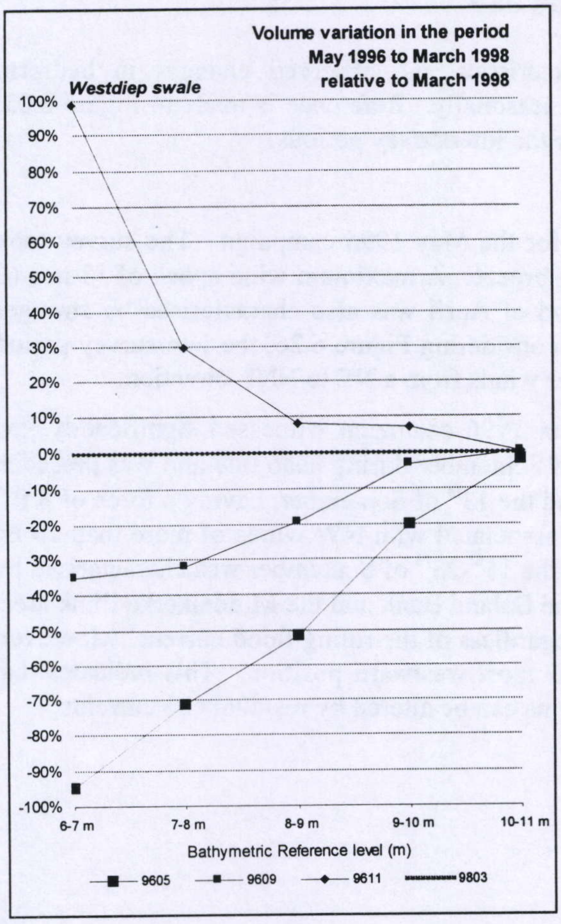


Figure 6.24 – Relative volume variations in the Westdiep swale.

The trends observed in the Baland Bank area are similar for the other areas, though some differences are apparent. Along the southern part of the Middelkerke Bank, the trends should only be considered from a depth of - 9 to - 10 m, as for shallower depths too much bias is imposed by randomness. Similar to the Baland Bank area, the September 1996 results are significantly lower than those of the other campaigns. The highest volumes are however observed for the November 1996 campaign. Contrasting to the Baland Bank area, is the decrease in volume as is manifested by the February 1997 results. As mentioned before, only a small box was used for volume intercomparison, comprising the transitional zone from the shallower dune area towards the Westdiep swale. Hence, it can not be excluded that upslope an accretional trend would have been observed. Also for the Baland Bank, there was a clear difference between the observed trends in the swales and along the dune area. The results of the September and the November 1997 campaign subsequently witnessed a decrease in volume, followed by an increase of sediments till March 1998. It is thus not clear to what extend the small area is representative for the southern part of the Middelkerke Bank. If the volumes in the larger box are compared, it is striking that deeper than - 9 m the same trends are found as in the small box. Shallower however, the trends are reversed and are similar to the observations along the Baland Bank area. In the Ravelingen area, the February 1998 results were lowest in volume. Consistency is also found along the Westdiep swale. Interesting are also the volume calculations for the May 1996 survey; these are significantly lower than the results of the September 1996 campaign.

6.4.4. Relation with the hydro-meteorological database

Similar to the temporal variation in grain-size characteristics, the observed changes in bedform morphology can at least to a certain extend be explained seasonally. Reference is made to Figure 6.03. Figure 6.25 represents the average wind characteristics for the intersurvey periods.

The trend is most significant for the Baland Bank area.

In the Westdiep swale, a sediment deficit was observed for the May 1996 campaign. The survey took place during spring tide in between two periods of strong breeze. A maximum wind speed of 13 m/s (6 Bf) was attained blowing from a NW direction. The end of April was also characterised by stronger winds, but merely blowing from a S direction. However considering Figure 6.26, the intersurvey period February – May 1996 was generally dominated by stronger winds from a NE to NNE direction.

For all the subenvironments, the results of the September 1996 campaign witnessed significantly low sediment volumes. That survey took place the 23rd-25th of September during neap tide and was preceded by 1-3 Bf, NW-SW winds. The last storm occurred around the 13th of September, having a force of 8 Bf, blowing from a NW to NNW direction. A severe storm associated with NW winds of more than 10 Bf took place the 28-29th of August. However, the period of the 15th-23rd of September was characterised by winds less than 6 Bf, mainly from an ENE direction. In the Baland Bank and the Middelkerke Bank area, the large to very large dunes were ebb-dominated (SW) regardless of the ruling flood current. Moreover, the crestlines of the dune structures were located in their most westward position. This indicates that despite of the flood dominance in the coastal zone, bedforms can be altered by residual ebb currents.

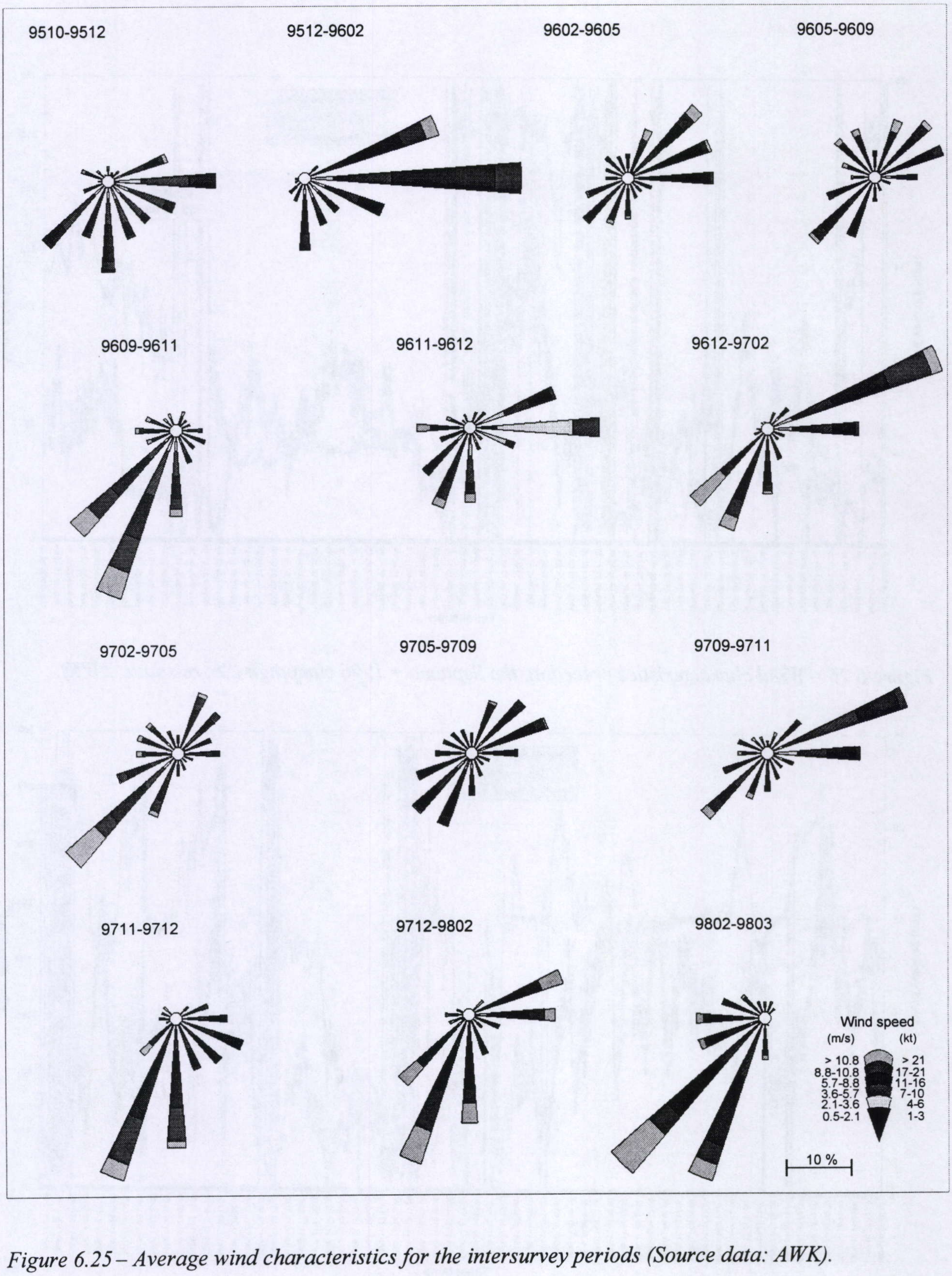


Figure 6.25 – Average wind characteristics for the intersurvey periods (Source data: AWK).

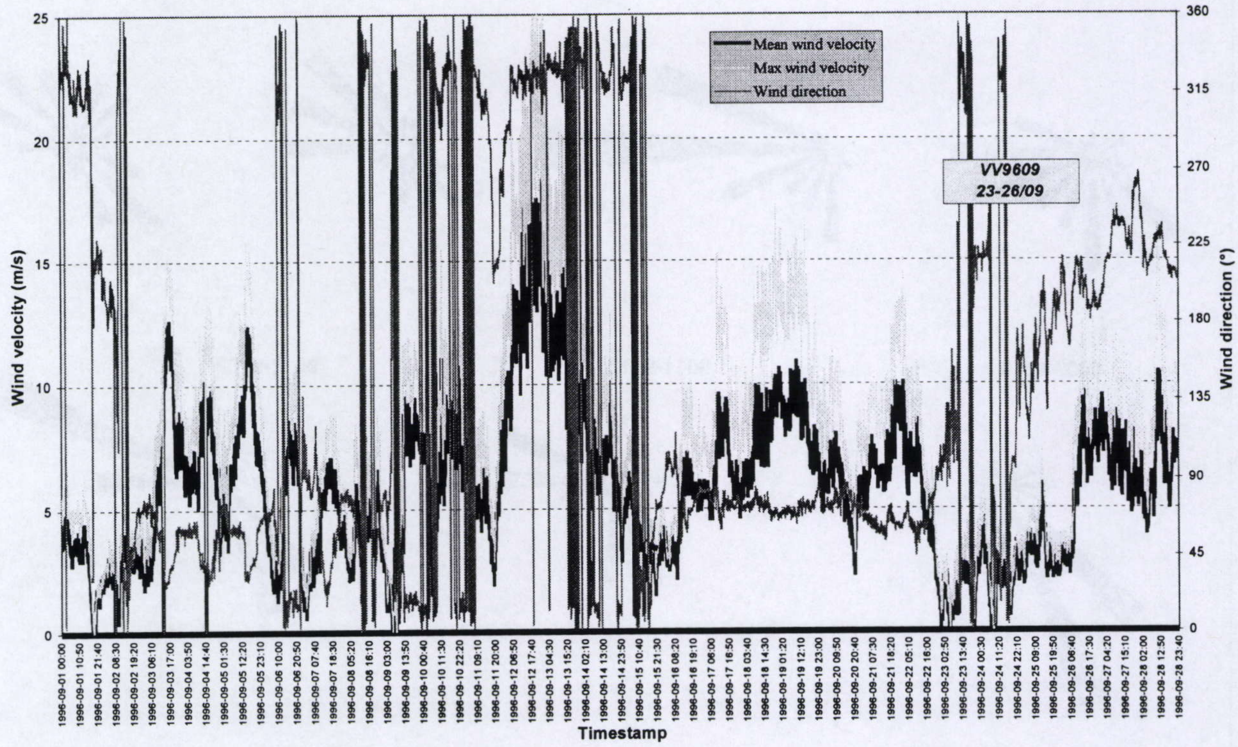


Figure 6.26 – Wind characteristics preceding the September 1996 campaign (Source data: AWK).

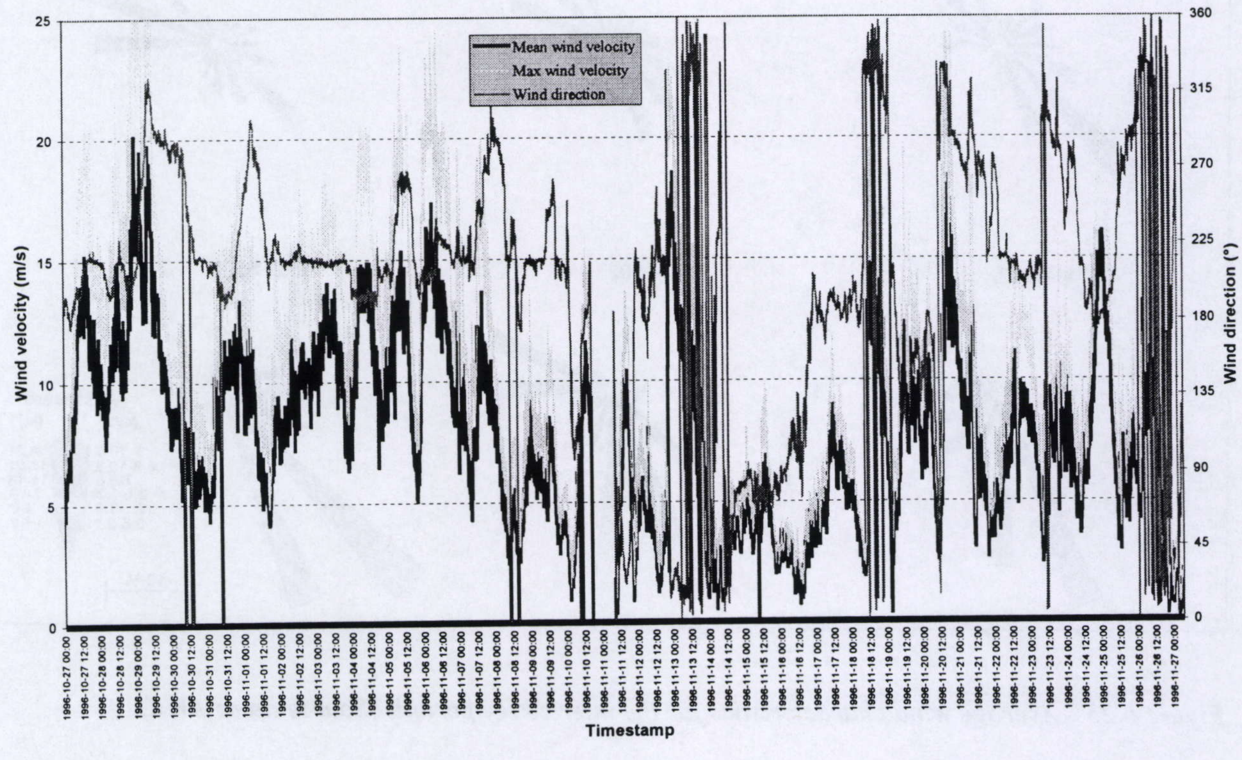


Figure 6.27 – Wind characteristics in November 1996 (Source data: AWK).

An analysis of the wind data between the September and November 1996 surveys, results in a fairly turbulent period of SW-NW winds. The average winds had a maximum force of 8 Bf around 28-29th of October. The conditions remained unstable and again 8 Bf was reached around the 20th of November. The survey itself was preceded by rough weather from a NW direction. This situation was associated with spring tide. Figure 6.27 shows a dominance of SSW winds significantly exceeding a force of 6 Bf. The sediment volumes increased significantly.

The intersurvey period November – December 1996 predominantly represents calm conditions. The winds blew predominantly from an E direction, but having a force of less than 4 Bf. The beginning of December was characterised by winds of up to 7 Bf from a SSW direction. The 7 days preceding the survey were characterised by winds from a NE to SSW direction, less than 6 Bf. The campaign took place during neap tide. A general decrease in sediment volume is observed.

For the Baland Bank area, the results of the February 1997 campaign showed the highest volumes. The highest frequency of winds blew from a ENE direction with a force exceeding 6 Bf. Still, stronger winds were far more apparent from a SW direction (Figure 6.28). Moreover, the month of February was characterised by an alternation of storm depressions. The averaged winds exceeded 9 Bf and blew mainly from a SSW direction. The campaign took place during spring tide.

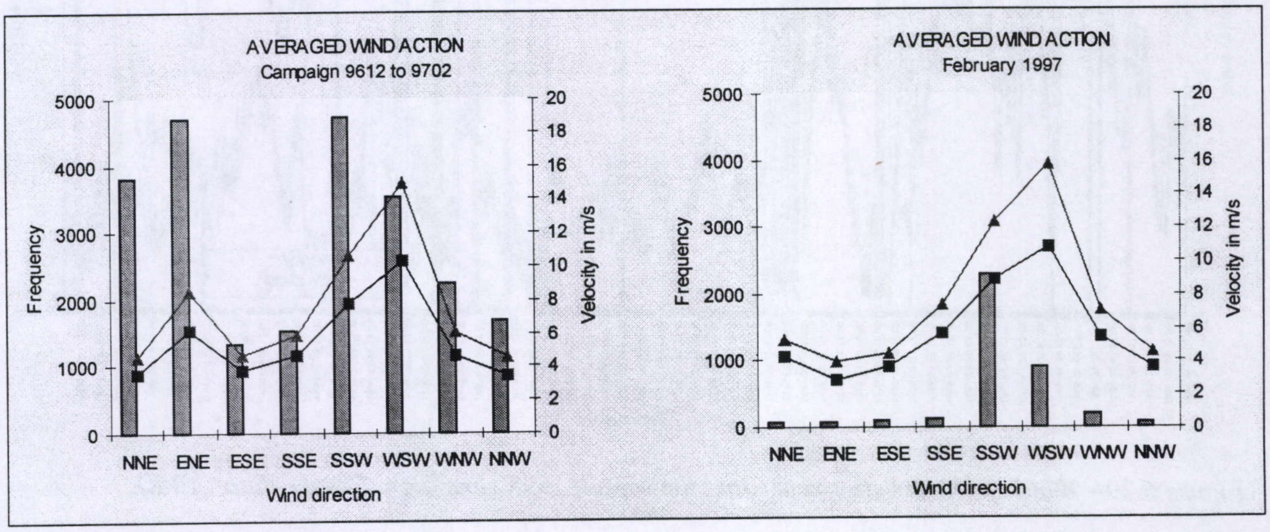


Figure 6.28 – Wind characteristics preceding the February 1997 campaign (Source data: AWK).

Throughout the observation period, the summer of 1997 represents the calmest conditions. No extreme wind forces were encountered, nor was the period characterised by preferential wind directions. At the end of August, a small depression occurred exceeding 6 Bf with winds blowing from a S to SSW direction. The September 1997 campaign took place during neap tide. As noted before, a strong decrease in sediment volume was observed.

The intersurvey period between the September and November 1997 campaigns was predominantly characterised by ENE winds, generally of less than 4 Bf. The strongest winds of force 7 – 8 Bf blew from a SSW to SW direction. Especially, the period 6 – 15th of October was fairly turbulent. The campaign took place under spring tide conditions. The sediment volumes were again much higher.

Generally, the February 1998 campaign is preceded by the most turbulent weather conditions throughout the observation period. Winds having a force of more than 6 Bf significantly blew from as well the SW to S sector as from the NE to E sector. The highest frequency is however associated with SSW winds (Figure 6.29). Especially, the period 1st– 13th of January was fairly rough and was characterised by winds of 8 – 9 Bf from a SSW direction. Around the 20th of January, the waverider at Oostende recorded wave heights of more than 3 m. These were associated with NW conditions. Another storm depression occurred around 24 – 26th of January. Winds of 7 Bf blew from a NE – ENE direction. The campaign was preceded by winds of a NW direction, slightly exceeding 6 Bf. The campaign took place during neap tide.

The March 1998 campaign is definitely strongly influenced by strong SSW to SW winds. Four major storm depressions occurred in the intersurvey period, all characterised by winds from a SSW to SW direction. The period 1st–13th of March was very turbulent; on March 11th, 9 Bf WNW winds were encountered. Wave heights recorded at Oostende, exceeded 3 m. The days preceding the campaign were merely dominated by NNW - NNE winds, slightly exceeding 6 Bf. The campaign took place during neap tide.

Both February and March 1998 results showed a decrease in sediment volume.

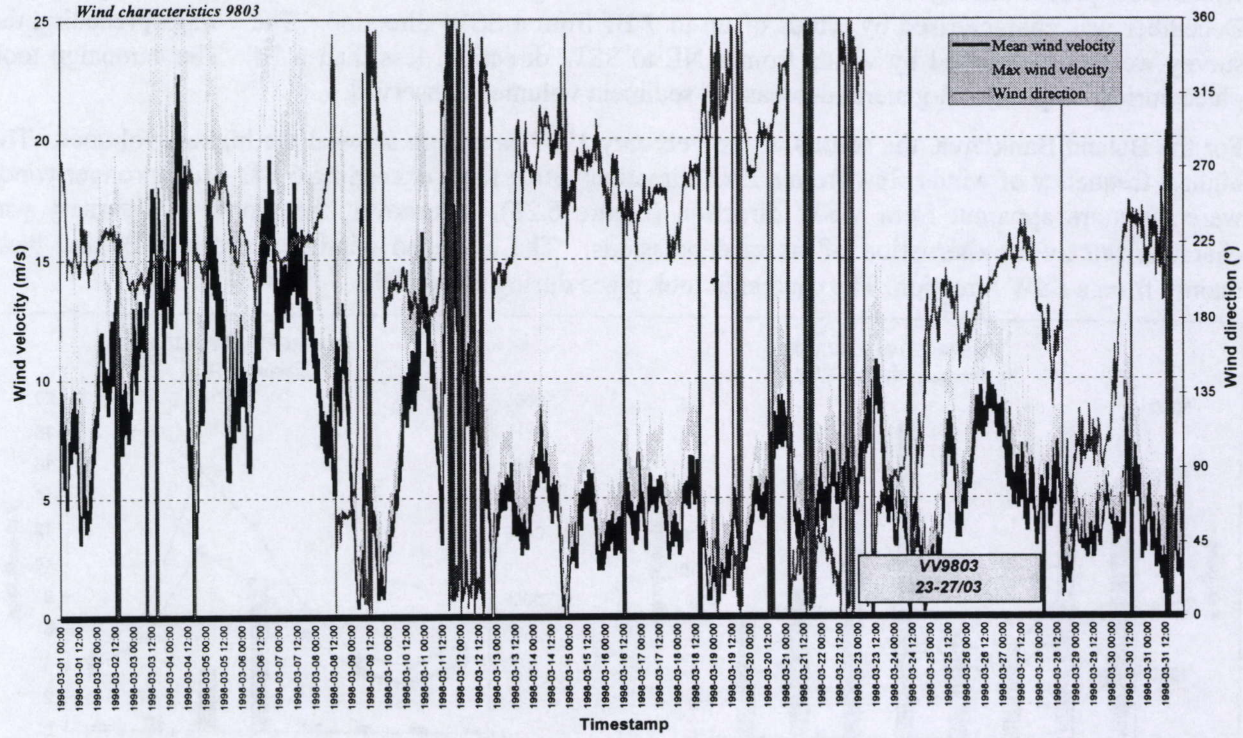


Figure 6.29 – Wind characteristics preceding the March 1998 campaign (Source data: AWK).

6.4.5. Summary and conclusions

From the evidence presented, it can be stated that there is a clear relation between the observed morphological changes and the ruling hydro-meteorological conditions. The volume variations along the Baland Bank show that the lowest volumes are generally associated with summer to autumn conditions, whilst the winter months witness the highest volumes. The sediment volumes in the spring period likely fall within the range of both. Related to the hydro-meteorological conditions, some conclusions can be drawn. They are particularly supported by the observations along the Baland Bank area, but are confirmed along the other environments:

- from the observations, it seems that the smallest sediment volumes are associated with periods of NE to NNE winds. These frontal winds are merely associated with erosion, especially along the interaction zone of the near coastal area and the Flemish Bank system;
- from the morphological changes, the impact of NE to E winds can not be fully shown. Such a situation was characteristic for the winter period 1995 – 1996. These winds likely enhance the sediment transport capacity of the ebb tidal current. If these winds persist in time, the reinforced ebb tidal currents are able to alter the bedform pattern. Still, under most circumstances, the crestlines witness the dominance of the flood current;
- winds blowing from an E to S direction are clearly inferior; hence, they are not considered important to explain changes in morphology;

- periods characterised by winds blowing from a SSW – SW direction are most interesting. As this wind direction aligns with the dominant flood current and with the general configuration of the swales, a lot of sediment can be advected along the swales. Generally, these situations are associated with an accumulation of sediments. However, if the current is strongly enhanced, hydraulic sorting processes are intensified. This explains the stability to slightly erosional trend along the axis of maximal force;
- storms associated with winds from a NW direction are generally the most severe, though as their duration is mostly short, their long-term effect can be minimal. Given the height of the waves associated with such events, it seems that the areas are flattened. Although this impact can not be fully estimated, these events likely evoke a destabilisation of the environment. The period following such an event will determine the morphological evolution.

Most events can be explained taking into account the above mentioned trends. Bias may be implied if an intersurvey period is characterised by winds of more than 6 Bf from a variety of directions. In this case, the last event will determine the morphological evolution. From the observations, it seems that the consistency and hence duration of such an event is more important than its strength. This was especially demonstrated by the results of the September 1996 campaign. Although the survey was preceded by some storm depressions characterised by strong winds from a NW direction, it seemed that merely the period just before the campaign, witnessed by ENE winds of less than 6 Bf, determined the morphological pattern. However, it is believed that this could only be accomplished as the area was destabilised by the NW conditions preceding the campaign. Remarkable is the decrease in sediment volume in the period following the November 1997 campaign. As the wind blew predominantly from a SW direction, a general accretional trend would be expected, but still a slight erosion occurred. Again, it is striking that a short period of consistent NE winds is capable of counteracting the generally expected trend. In the case of the March 1998 campaign, a few events of NW winds changed the residual pattern. It should be noted that during the winter months, sediment transport by the combined action of currents and waves is intense. This was also shown by the temporal grain-size differentiation.

It has to be emphasised that from the sediment transport calculations, it was demonstrated that the tidal currents alone are competent to transport sediment. From the differentiation in grain-size characteristics it was shown that indeed the hydraulic sorting processes are intense, and thus the seabed is easily reworked. The intensity of the hydraulic sorting processes can also be deduced from the morphological evidence. Although the November 1996 campaign witnessed an overall accretional trend, the crestal zones merely lied within the stability range. This means that although the conditions were rough throughout the period preceding the campaign and the fact that a lot of sediment was brought into the system in a short period, the tidal currents already hydraulically sorted the amount of sediment. Moreover, the samples taken along the area, did not show significant differences and the same processes could be deduced from the sediment texture. Apparently, stormy periods associated with strong SW winds do not introduce significantly different sediments. This evidence also implies that the observed changes, being as well erosional as accretional, are part of a normal process.

During the summer months, the bedforms are relatively stable. Generally, a combination of low waves and low neap tides can leave the bed undisturbed. This may also be enhanced by intermittent benthic anoxia (JAGO et al. (1993) in: HUNTLEY et al. (1993)).

Although there is a clear difference in dynamics between spring and neap tide, changes imposed by these forces seem to be inferior to the processes on a larger scale. Still, spring tide conditions are needed to entrain a major amount of sediment. It is evident that when storms coincide with spring tide, the largest changes in sediment volume is expected.

As was mentioned above, the four subenvironments react more or less in the same way upon the ruling hydro-meteorological conditions. Hence the trends valid for the Baland Bank area can be extrapolated towards the other areas. Along the southern part of the Middelkerke Bank, it is quite surprising that the trends observed for the shallower area north of the - 10 m contourline resemble the trends found along the Baland Bank, whilst south of it a reversed trend is noticed. This is likely linked with the general configuration of this environment. Towards the south, the Middelkerke Bank merely resembles a plateau-like morphology and is most likely affected by intense sorting processes that are also acting along the slope of the Westdiep swale. The shallower area is as well influenced by residual forces linked with the Westdiep swale, but also by residual forces channelised by the ebb-shaped Uitdiep swale. The counteraction of flood and ebb residual forces is as well important for the Baland Bank as for the southern part of the Middelkerke Bank. As witnessed by the chart differencing results, the smallest volumes for the February 1998 campaign along the Ravelingen, are mainly associated with the erosional trend of the northern dunes. To the south the trend was merely stable. From this, it can be concluded that the northern part of the Ravelingen is most vulnerable to NE-ENE conditions. The 7 Bf, NE-ENE winds in the period of 24 – 26th of January 1998 clearly had a devastating effect on the area. The sandbank – swale system could easily recover due to a normal supply of sediments being maximal along the direction of the main axis of the swale. Unlike the Baland Bank, the Ravelingen area is further away from the sediment source. Moreover, the tidal currents in the northern branch of the Westdiep swale are not as competent as those interacting with the Baland Bank area.

From the chart differencing and the temporal grain-size variations, it can be supported that SW storms are associated with bedload and suspended load transport. The importance of the latter is proven by the accretional trend observed after a stormy period. It is believed that the transported amount of sediment also dampens the turbulence and hence the erosion that would normally be associated with such strong wind forces. However, this might be the case during the rougher winter months. NE storms are generally associated with erosion. As the tidal currents from that direction are weaker, the wave movements may become more important. Moreover, as no sediment input is expected from that direction, it may be deduced that NE winds need not to be as strong to induce morphological changes.

Regardless of the significant accretion trend observed between the September and November 1996 campaigns, no real differentiation is seen between the surficial samples of the November 1996 and the other campaigns. It seems plausible that this is merely indicative of a deposition of sediments that is been subjected to intense hydraulic sorting processes, and that the amount of sediment is likely redistributed fairly rapidly. Moreover, this indicates a fairly homogeneous input of sediment.

From the observations, the near coastal area seems to recover fairly quickly from stormy periods. This was indeed expected from the sediment transport calculations in Chapter 4. Still, a lag in the recovery time is seen between the area aligning with the axis of maximal force and the areas just north or south of it. This was especially demonstrated along the interaction zone of the near coastal area and the Flemish Banks.

6.4.6. Discussion

Generally in the literature, stormy conditions are associated with erosive events (HUTHNANCE (1982a); STRIDE (1988)). It seems indeed likely that sandbanks undergoing strong tidal and wave action are partly flattened and that the sediments are largely reworked. Also HOUBOLT (1968) mentions that the crests of sandbanks are likely disturbed during stormy conditions, but that they also seem to restore their equilibrium fairly rapidly. TERWINDT (1971) specifically discussed the effects of wave flattening on the larger bedforms.

On the basis of detailed morphological investigations of pre-storm and post-storm data of the Middelkerke Bank, HOUTHUYS et al. (1994) showed a lowering of the crests of the large dunes by up to 1.2 m, whilst an accretional trend was found along the lower part of the steep flank. The latter was interpreted as being derived from the shallow parts of the sandbank during storms. On a sedimentological level, as well coarsening as fining of grain-sizes were observed. In respect to the fair-weather conditions, the NW flank shows a coarsening trend, whilst the landward SE flank merely shows a fining. From this, it was put forward that waves approaching the sandbank from the N, cause an extra winnowing on the exposed flank of the bank whilst the SE flank is better protected against wave action.

VINCENT et al. (1998) investigated the importance of storm wave resuspension relative to the 'normal' tidal current suspension, mainly to assess the processes by which the bank is maintained. From the estimation of suspended sand transport at two sites on the Middelkerke Bank, it was suggested that sand resuspension was mainly due to waves, and that transport was dominated by a few hours when large waves coincided with peak flood currents. The sand transport rate on the steep slope of the bank was relatively high, and was directed according to the major axis of the tidal ellipse. The sediment sizes involved varied between 100 – 140 µm. As these sizes did not occur in any significant proportion in the *in situ* sediments, it was concluded that they were advected from deeper water. From the observed up-slope sediment transport during storms, it was suggested that waves play an important role in the maintenance of the bank and that they are not simply the mechanism preventing a continual growth.

The evidence presented in this chapter shows that under stormy conditions, the near coastal area is fairly stable. Winds blowing from a NW and NE sector generally evoke erosion, whilst SW conditions merely bring in sediment. The residual effect is however determined by the duration of the destabilisation. Hence, periods of NE winds of only moderate force can be equally erosive as storm depressions of a short duration. This is an implication of the quick recovery time of the near coastal area, governed by a fairly easy supply of sediment.

As outlined in DYER & HUNTLEY (in press), it is believed that although waves might be an important process locally, they may not be on a regional scale. However, it seems that the interaction between the shape of the bank and the hydrodynamics must lead to an equilibrium configuration in order for the bank to be stable and self-sustaining when the sand is still mobile. From the variability in the sand supply, and in the storm-induced wave and surge currents, it is sometimes difficult to define how close to equilibrium a sandbank may be.

The homogeneity of the sediments pleads for a constant source of sediment. It is believed that most of the sediment is just recirculated. However, it sounds also plausible that the sediment is also derived from the nearshore zone, west of the area.

From chronosequential measurements along the shoreface and beach east of Dunkerque (FR), CORBAU et al. (1999) deduces mainly shoreface erosion during N frontal winds and WSW winds associated with spring tidal currents. The latter conditions may induce accretion on the beaches.

Given the dominant eastward littoral drift, it seems likely that indeed sand from the French sector is transported towards Belgium. Since the velocity of the tidal currents gradually decreases in that direction, the WSW to SW accretion in the Belgian sector can be explained. This is supported by a similarity in grain-sizes. CORBAU et al. (1999) reported grain-size values ranging from 125 µm to more than 600 µm for the nearshore zone west of Dunkerque. It needs emphasis that the subtidal sandbanks in front of the French sector are coastwards migrating at a rate of 1 to 5 m/yr (CORBAU et al. (1993)). Hence, part of the reworked sediments is likely transported in an eastward direction by the tidal currents.

6.5. *Long-term morphological changes*

6.5.1. Introduction

In the following paragraphs, some hypotheses are put forward on the long-term morphological evolution of the sandbank – swale system under consideration. It needs emphasis that in the framework of this study, no additional data on this topic was assembled; hence the suggestions merely remain speculative and need further investigation. Reference is made to the authors mentioned in Chapter 2, Section 2.4.3 on the Quaternary development of the near coastal area. The development of the Dutch (and to a certain extend the Belgian) coastal zone in response to changing oceanographic conditions and differential vertical subsurface motions, is presently being investigated by the Netherlands Environmental Earth System Dynamics Initiative (NEESDI). VAN DER MOLEN (1998) focusses on the present and palaeo-hydrodynamics and sand transport in the North Sea, whilst VAN DIJCK (1999) investigates the Holocene coastal evolution in the southeastern part of the North Sea (Belgian and Zeeland coast).

In a first paragraph, some aspects of the geological evolution will be discussed, whilst secondly some prediction will be made on the future evolution of the coastal system.

6.5.2. Geological development

6.5.2.1 Coastal evolution

On the basis of the literature and compiling the evidence resulting out of this study, a hypothesis can be put forward regarding the origin of the sandbank – swale system under investigation.

Generally, it can be sustained that the temporal and spatial variability of processes in a nearshore environment, typically produce bedforms with complicated internal structures (ALLEN (1980b)). This can be easily demonstrated along the Flemish Banks where a range of sediments is available, potentially giving rise to boundary layers (HOUTHUYS (1990), TRENTESAUX et al. (1992)). Mostly, also the large to very large dunes can be recognised in the fossil record due to their migrational behaviour exemplified by cross-bedding (e.g. BERNE et al. (1988)). The preservation potential of the lee slopes of subaqueous dunes is much higher than the corresponding stoss slopes (SMITH (1988c)).

However, as outlined in the previous chapters, the sediments in the near coastal area are far more homogeneous. In the most dynamical areas, the sediments are continuously being reworked by intense hydraulic sorting processes. Hence, no real stratification can be perceived. As put forward by VAN DE MEENE (1994), sandbodies characterised by the combined flow facies, are generally difficult to recognise in the fossil record on the basis of their sedimentary structures alone.

Seismic sections in the near coastal area, learn that the upper sandbank reflectors dip in a coastward direction (Fig. 6.30) (HENRIET & DE BATIST (1983); DE MAEYER et al. (1985)). The profiles reflect that the sandbanks tend to migrate in that direction, though as outlined in Chapter 4 and confirmed by observations reported in the Chapters 5 and 6, the flood current is competent enough to transport sediment on a regular basis. Hence, any natural progradation in a coastwards direction will be counteracted by the sediment transport capacity within the swales. It is believed that the enhanced dynamics in the Westdiep swale were characteristic for a significant time period as demonstrated by the thickness of the Quaternary deposits in the near coastal area (Fig. 6.31). In the Westdiep swale and the Kleine Rede, these deposits are less than 10 m. The Tertiary strata are even eroded. This is also demonstrated in Figure 6.30.

The idealised interpreted seismic profile presented by WARTEL (1989) provides a framework for the genetic evolution of the near coastal area. From his study, he puts forward a number of facies that are characteristic for a tidal flat environment (also Section 2.4.3). As mentioned in the previous chapter, boxcores have been taken along this profile to verify its surficial sediments (Fig. 6.32).

The boxcores primarily witness three facies. The upper sands can be considered fully marine sands. As demonstrated throughout this study, the sediments predominantly consist of well-sorted fine to very fine brownish sands. These are likely intercalated with silty to clayey sediments, in water depths deeper than - 7 m. In the Grote Rede swale, an enrichment of mud is most likely. Along the Baland Bank, medium sands rich in shell fragments, can be observed. However, the occurrence of such a facies can be explained by the present hydrodynamic regime (Section 5.4). Most peculiar are the surficial sediments along the Westdiep swale, separating the Middelkerke Bank from the Coastal Banks. Boxcores 3, 4 and 5 witness a mixture of sediments composed of shelly material, occasionally a pebble, fine and medium sands and generally enriched with mud. In boxcore 4, these deposits overly fine grey sands. In boxcore 5, a distinct clay layer can be observed. From the nature of the sediments, these deposits could be associated with a tidal flat environment, characterised by tidal gullies and an alternation of sandy and muddy deposits. On the basis of the hydrodynamics and the observations throughout this study, it can not be sustained that these deposits are allochtonous. Their exposure is however an indication that this swale is presently being eroded and reworked. It is also believed that the boxcores taken in the Kleine Rede swale represent muddy tidal flat deposits (Fig. 5.18). Given the current strength in that swale, it seems very unlikely that such clayey deposits would represent a modern sedimentation. Moreover, their compaction makes them fairly hard to erode. It is believed that only the upper few cms, consisting of fine to medium sands, are representative of the current regime. Still, without ^{14}C datings this remains speculative. The fine grey sands are likely of Early-Holocene age. The transition of the surficial sediments from medium brown sand towards the fine grey sands has been described by VAN DE MEENE (1994). VAN DE MEENE (1994) states that this forms part of a coarse-fine-coarse sequence going from the nearshore zone through the shoreface to the inner-shelf. The medium brown sand belongs to the offshore sand sheet facies, described by STRIDE (1982). This sand sheet may thin, forming a shell-rich lag deposit, overlying the grey sand.

Radiocarbon-dated, ground-truthed seismic profiling evidence from the Middelkerke Bank (DE BATIST et al. (1993); TRENTESAUX et al. (1993); STOLK (1996)) shows the presence of tidal flat deposits on top of Pleistocene deposits but underneath fully marine sediments, the latter being correlated with a sandbank facies and generally constituted of fine to medium brownish sands. The tidal flat deposits identified in the Middelkerke Bank area, show a diversity of sediments and sedimentary structures (STOLK (1996)). Decimetres thick layers of shells and shell debris are found correlatable with the dynamics of tidal gullies and channels (EISMA et al. (1981)). Typical for tidal flat deposits is also the alternation of sand and clay layers (REINECK & SINGH (1980)). They are likely of Early Holocene age (STOLK (1996)). It needs emphasis that the rapid sea-level rise during the Early Holocene was likely associated with strong reworking processes, hence eroding the older deposits.

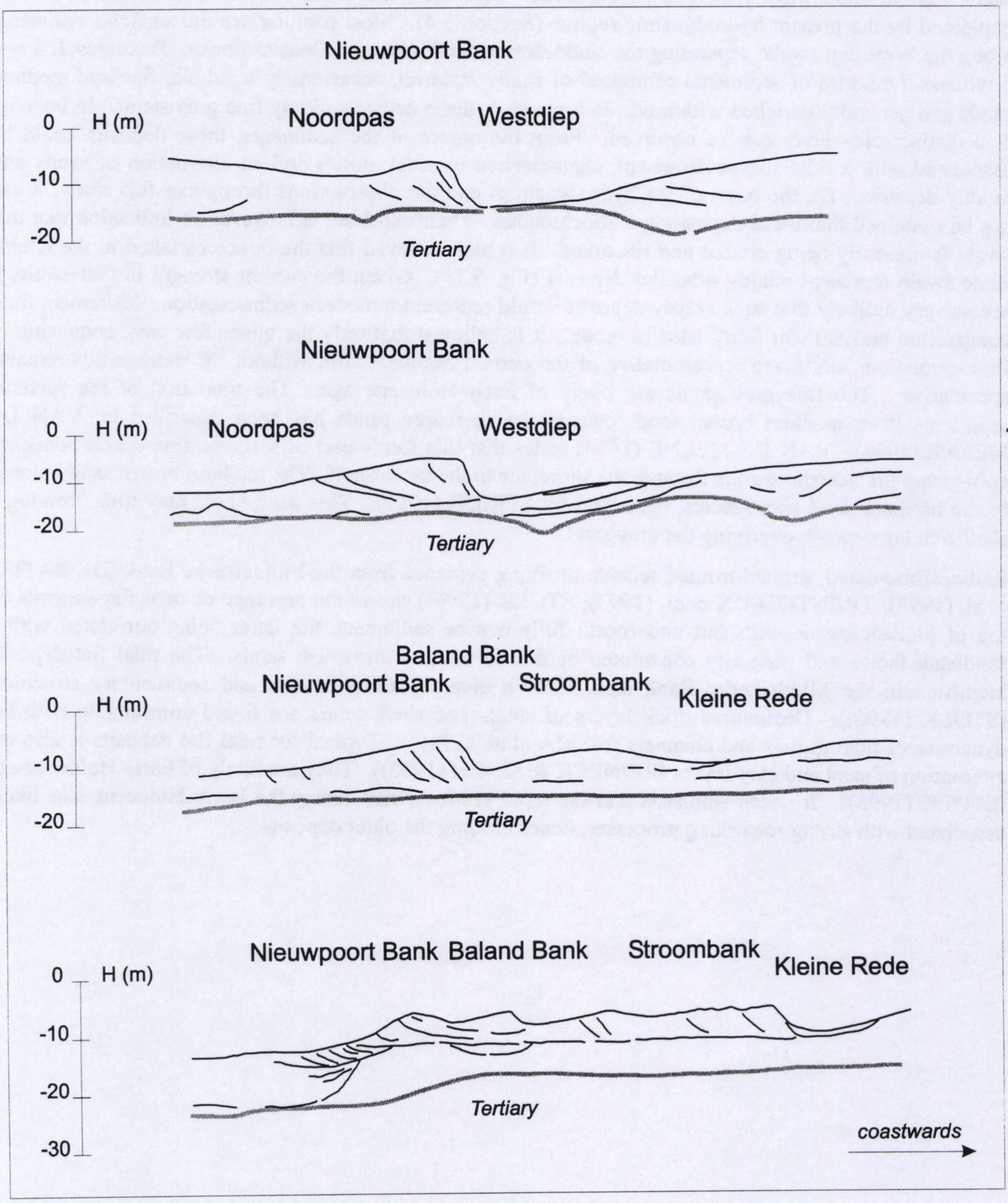


Figure 6.30 – Seismic profile (HENRIET &DE BATIST (1983)).

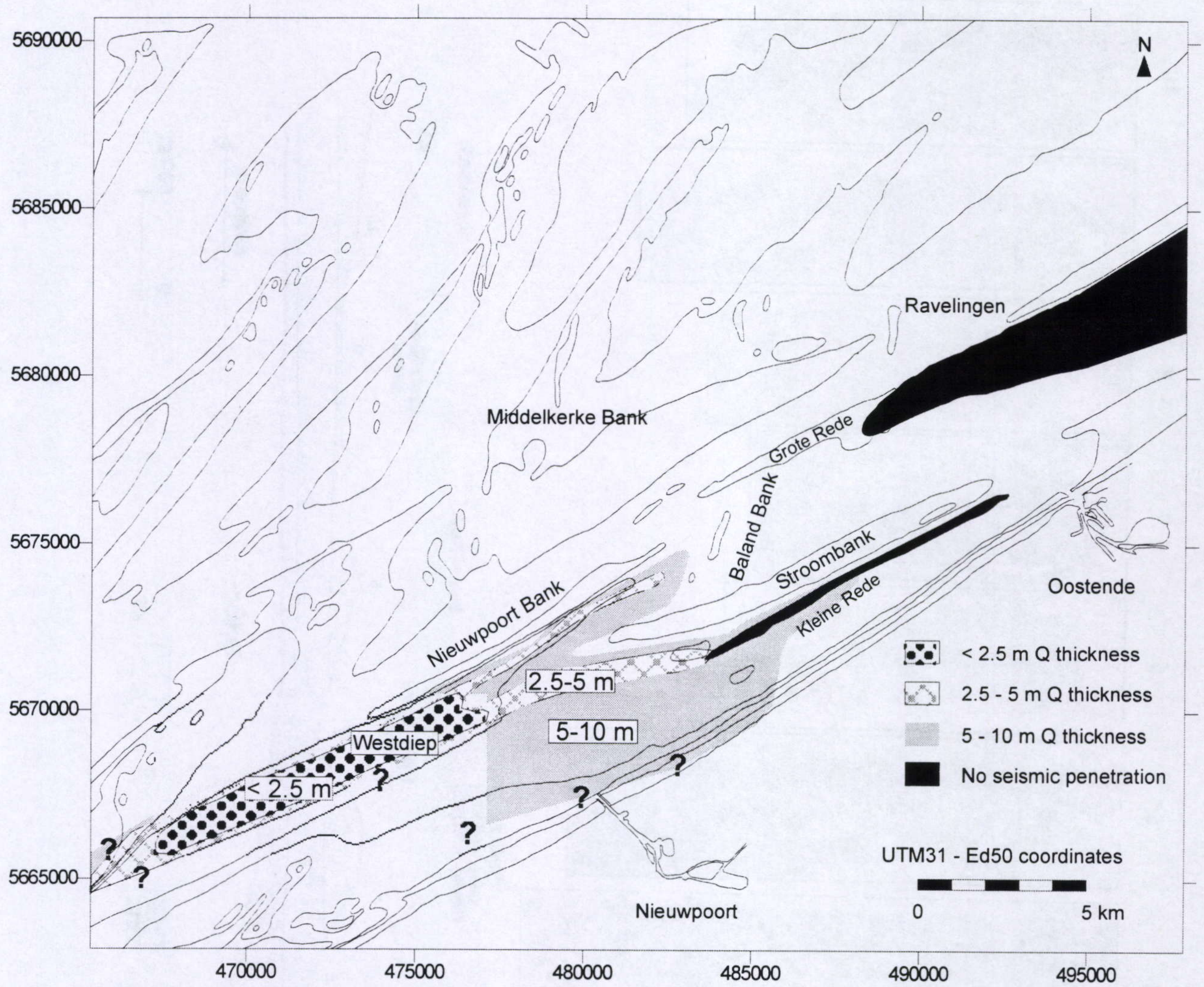


Figure 6.31 – Indication of zones where the Quaternary deposits are less than - 10 m (modified from MARECHAL & HENRIET (1983)).

It is believed that the initial stages of the formation of at least the Stroombank is situated in the period 5000 to 2000 BP when the coast was stationary to advanced, meaning that the evolution of the coast and the spatial variability was determined by sediment availability and transport (VAN DER MOLEN (1998); VAN DIJCK (1999)). This means that the sandbanks are modern features that are formed, shaped and maintained by processes similar to the present hydraulic regime. It is believed that the origin of the Coastal Banks resembles that of the shoreface-connected ridges off the Holland Coast. The formation of the latter comprises two phases: a subrecent one that started around 3400 ^{14}C BP or afterwards, and a recent one starting at or after 1100 ^{14}C BP (VAN DE MEENE (1994)). The latter is probably still going on at present. VAN DE MEENE (1994) also mentions that the subrecent phase occurred during the progradational phase of the coastal barrier, whilst the recent phase corresponds with the regressional phase of the barrier. Still, those sandbanks occur in water depths of - 14 to - 20 m and are less pronounced in morphology.

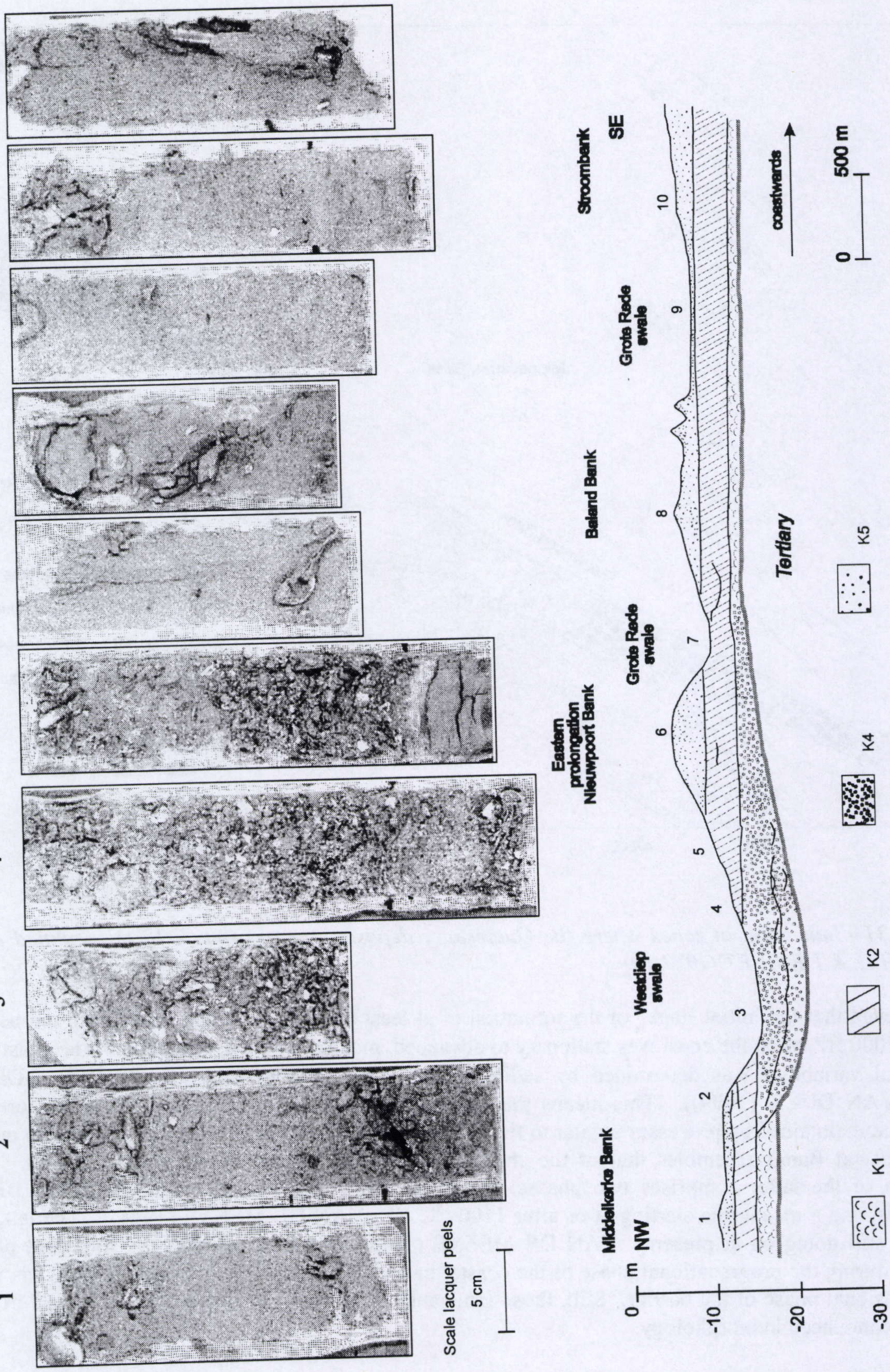


Figure 6.32 – Seismic profile covering the southern part of the Middelkerke Bank – Baland Bank – Stroombank (WARTEL (1988)). In the framework of this study, boxcores have been taken along the profile. (Legend see text, also Section 2.4.3).

6.5.2.2. Hypothesis on the sandbank formation

From the evidence presented for the genesis of the Middelkerke Bank (see above) and the shoreface-connected ridges off the Holland coast (VAN DE MEENE (1994)), the formation of at least some sandbanks is polygenetic and depend on a number of events that are often difficult to situate in time.

Generally, the question remains whether they are relict features created during the sea level rise of the Holocene transgression or whether they formed as a response to the hydrodynamic and sediment regimes similar to those presently active (i.e. ZIMMERMAN (1981); HUTHNANCE (1982a); DE VRIEND (1990)). Still, the presence of a relict morphology does not necessarily imply an interdependancy with the sandbank formation.

In contrast to the Flemish Banks, it seems likely that the origin and evolution of near coastal sandbanks is largely dependent on the configuration of the coastline.

As outlined by DYER & HUNTLEY (in press), sand ridges or linear sand banks predominantly occur in areas characterised by rectilinear currents. Sediment may be transported both as bedload and as suspended load, the latter especially when waves are present. The sand is produced either from erosion of the sea bed or from coastal erosion. The coastal erosion may be caused by rapid coastal recession, and this can potentially isolate the bank from its source of sediment, exposing it to a different flow regime that may lead to a drastic modification as it moves towards a new equilibrium state.

In the perspective of coastal retreat and sea-level rise, it seems indeed probable that the near coastal sandbanks can be classified as alternating or en-echelon banks associated with a recessional headland (DYER & HUNTLEY (in press)). On the basis of the shoreline retreat theory of SWIFT (1975), the multiplication sequence of CASTON (1972) and HARRIS & JONES (1988), the following evolution is hence proposed:

1. it is supposed that the sands forming the Stroombank resulted from headland erosion, as well from the east as from the west; thus creating a sand stream convergence; this could be accomplished near the 'Pointe de Wenduine' (headland); as outlined in SWIFT (1975), sand is swept towards a headland as the coastline retreats and continues to do so until there is a balance established between the shape of the headland, the longshore transport rates to its tip, and the loss of sediment to the banks; the resulting shore-attached sand bank develops at an angle to the coast in the direction of the dominant transport; the transport in the landward trough can result from tidal currents augmented by surge currents and waves;
2. it is believed that the main sand supply originated from the east (Westerschelde area); the Stroombank thus elongated in a western direction (creation of the bank by an excess of sand supply); probably, sand also originated from the sediments eroded during the large-scale retreat of the older coastal barrier, the latter forming a sediment buffer along the shoreface; it seems also likely that the coastal barrier formed at that time also provided sediment; the whole was likely subdued to intense hydraulic sorting processes and swept by wave action;
3. considering the historical evolution from 1600 onwards as outlined by LIGTENDAG (1990), it is remarkable that especially the coastal stretch between Westende and Oostende (offshore corresponding to the Stroombank) suffered mostly from erosion; from that evidence, the coastal retreat was high during the period 1600 to 1750 (Fig. 2.08);
4. the steep landward face of the Stroombank already indicated the erosive nature of the flood current; the transport in the landward trough could result from tidal currents augmented by surge currents and waves, and is similar to the mechanism of the shoreface-connected ridges; the main difference between the two types remains the difference in importance of tidal currents (DYER & HUNTLEY (in press));
5. as the flood current increased in importance and as the Stroombank elongated, at some stage the westernmost part might have become unstable and too vulnerable to the flood;
6. from this point the system may have been partly evolving as the sequential stages mentioned in CASTON (1972) (Fig. 6.33);

7. possibly, the westernmost part of the Stroombank became isolated and gradually evolved into the Nieuwpoort Bank: note the strongly curvilinear appearance of the Nieuwpoort Bank on the map of STESSELS (1866) in contrast to the strong linear appearance of the Stroombank; still the map also shows a strongly invaginated - 6 m isobath along the stoss slope of the Stroombank, likely due to strong tidal currents; the area of the Baland Bank formed at that time the navigation channel 'Passe du Nord-Est', but it remains unclear whether this pass was artificially maintained or whether it was the major pathway for the flood current at that time; also around 1934, the Nieuwpoort Bank still showed a strong curvilinear appearance (VAN CAUWENBERGHE (1971));
8. it is believed that the dredging of the eastern part of the Stroombank for the clearance of the entrance of the harbour of Oostende, hence the creation of a navigation channel, has disrupted the equilibrium of the sandbank – swale system;
9. the opening of the eastern part of the Kleine Rede, could imply that the flood current increased in importance;
10. as it seems likely that the Baland Bank area was formerly dredged for navigational purposes, the ebb and flood dominated channels could become competent and evolved into a mutually evasive system, at the head of which sand could accumulate, hence initiating its development; the sandbank was firstly mentioned on the hydrographic maps around 1924-1929 (VAN CAUWENBERGHE (1971));
11. the initiated reorganisation of the available sand supply probably led to an enhanced current-seabed interaction along the Baland Bank area which in turn could lead to an overcapacity of sediment laden flows to be deposited in areas characterised by a convergence of flood and ebb residual flows;
12. it is assumed that since then, the equilibrium of the sandbank – swale system gradually re-established, by adjusting itself to the regional tidal current field; the sandbanks are thus an expression of an equilibrium maintained within an active sand transport path;
13. the excess of sand supplied to the system possibly accumulated in a berm-like morphology as an eastern extension of the Nieuwpoort Bank ('flood arm').

Point 1 and 2 remain highly speculative as no real evidence can be provided at this time. Still, it is believed that anthropogenic influences had a role in the coastal development, especially for the evolution of the Baland Bank area.

According to CASTON (1972) (Fig. 6.33), the complete cycle would result in three sandbanks where there initially was only one. DYER & HUNTLEY (in press) argue that if the innermost bank can not shift inshore to any extent, there might be a resulting fairly massive transfer of sand seawards where it is subjected to the offshore hydrodynamic regime.

As believed for the shoreface-connected ridges off the Holland coast (VAN DE MEENE (1994)), the banks would gradually extend offshore and eventually become separated from the retreating headland as the flood channel deepened. However, for the Coastal Banks it is believed that a tendency for a coastwards migration would be more important. This can be supported by the coastwards dipping internal reflectors, which might indicate a wave dominance of the sandbank at the time of formation. Moreover, as demonstrated throughout the preceding chapters, the relatively strong tidal currents merely induce a coastwards sediment transport.

It is not clear what timescale is involved in the generation of the sandbanks, and how that relates to the rate of coastal erosion and the variation in the physical processes. Due to its shallowness, it is obvious that the system continually interacts with the hydrodynamical agents and hence represents a fairly modern origin.

From calculated transport rates along two sites of the Middelkerke Bank, VINCENT et al. (1998) deduced a time-scale of 100 to 1000 years for its formation. Thus, the sandbank may respond and evolve on a time-scale of centuries to changes in equilibrium conditions.

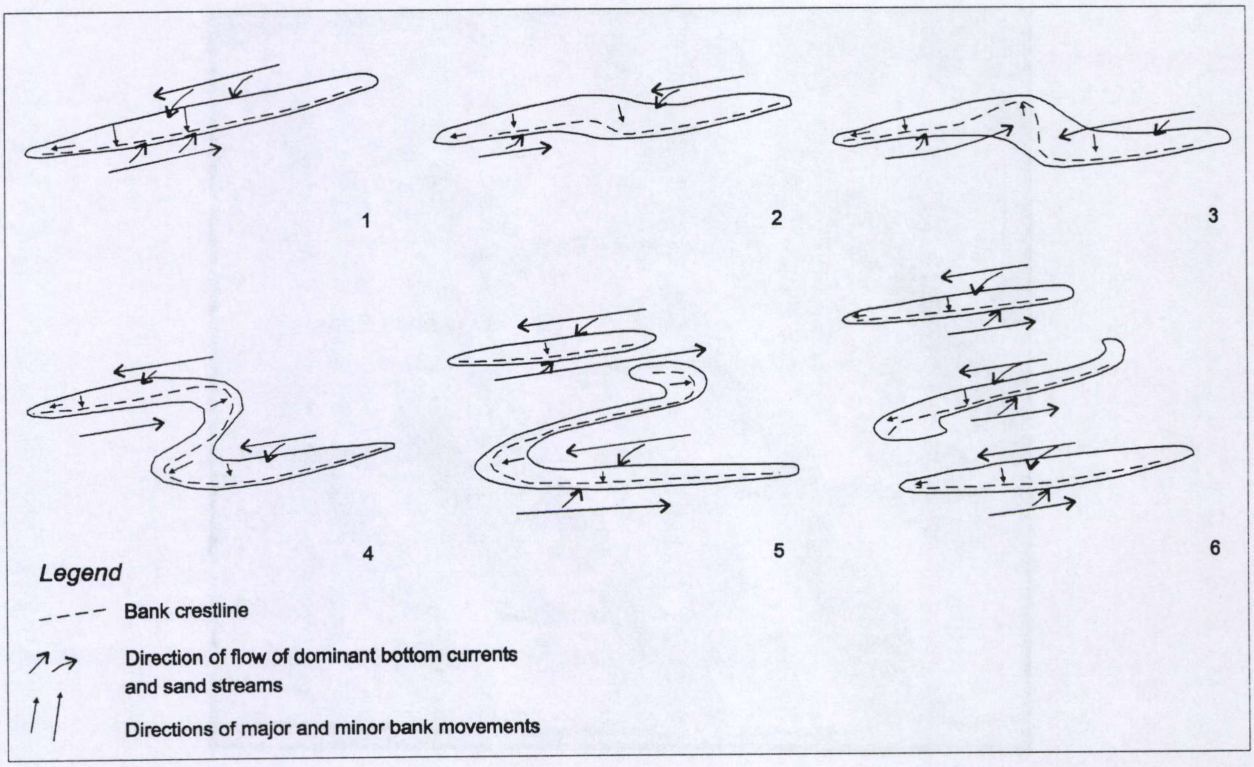


Figure 6.33 – Diagram showing the stages in the growth and development of linear sand banks (modified after CASTON (1972), adjusted for the present coastal system).

6.5.3. Prediction of long-term changes

In the coastal area off Nieuwpoort – Oostende, MACDONALD & O'CONNOR (1996) numerically modelled the variations in wave energy according to a continuing sea level rise. Several wave conditions and sea level rise scenarios were tested under the assumption that the sandbanks do not respond quickly to rises in the mean sea level. From the predictions, it seemed that the average wave energy impacting on the coast would increase in the order of 10 % by the year 2130. Moreover, the model results show that removal or lowering of the banks (i.e. by sand mining) would lead to an increase in the incident wave heights, and the existing balance between accretion and erosion could be tilted towards the latter, causing the coastline to recede. Also, the MINISTERIE VAN DE VLAAMSE GEMEENSCHAP (1993) mentions an increase of 10 % in wind speed and a 10° change in direction in function of global warming.

Figure 6.34 is an example of how the length of the incident wave, relative to the bathymetry, focusses the wave field. The sandbanks and shoals refract the waves and concentrate the energy on the headland, affecting the coast erosion rates (SWIFT (1975)).

Remarkable is the convergence of the wave field around the Kwintebank and the Middelkerke Bank by refraction. A zone of convergence is also seen at the steep slope of the Middelkerke Bank. Towards the coast also patterns of low energetic circumstances can be distinguished. This is especially striking along the coast where zones of higher and lower energy are alternating. The Baland Bank area seems to be more or less protected by the adjacent Nieuwpoort Bank.

A change in the configuration of the coastal system could lead to changes in the wave field. Hence areas that were formerly protected can be eroded again. SWIFT (1975) demonstrated how a detachment of a sandbank can lead to renewed erosion in an area formerly protected by the banks.

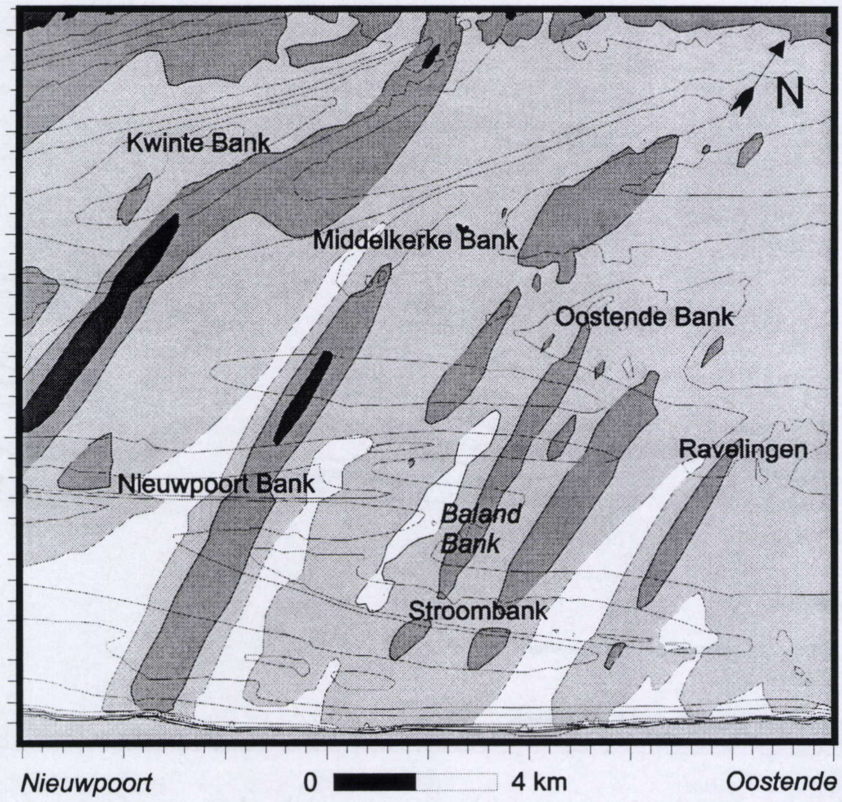


Figure 6.34 – Contour map of a normalised wave height (H/Hi) for a wave having a significant wave height of 1.5 m, a period of 5 s and an angle of incidence of N90°W (H/Hi diminishes from dark to light) (MACDONALD & O'CONNOR (1996)).

CORBAU et al. (1999) investigated the shoreface-to-beach system of the 30 km long coastal area extending from Gravelines to the French-Belgian border. The relation of wave patterns to coastal erosion was stressed and two types of erosion were identified, comprising the action of frontal waves and the combined interaction of tidal currents and wind. This leads to a recognition of five hydrodynamical cells along the shoreface. The corresponding segmentation was attributed to the specific distribution of the wave energy along the coast due to the presence of submarine sandbanks responsible for the deformation of the wave propagation. The alternating pattern of energy concentration and dissipation was most apparent for NNE-NNW incident waves. For WSW incident waves, the alternation disappears as are the cell boundaries. From this, CORBAU et al. (1999) conclude that such conditions enhance the sediment movement between the different cells.

6.5.4. Conclusions

The relative sea-level rise is a focal point in the discussion on the long-term morphological changes. Throughout the Holocene transgression, the area evolved from roughly a tidal flat to a fully marine environment. The sediments found in the near coastal area, represent both the fossil and modern environment, though given the sediment transport potential, also the older sediments are being reworked by the present hydraulic regime.

The Coastal Banks are thought to be formed by modern processes similar to those building up the shoreface-connected ridges off the Holland coast (VAN DE MEENE (1994)). Their origin is likely constrained to a time period having hydrodynamic characteristics comparable to the nowadays situation.

Although their origin may have been dependent upon storm conditions, their present morphological and sedimentological characteristics are tidally dominated. Hence, a classification as storm-dominated ridges (SWIFT (1975)) seems not really appropriate. Moreover, the theories of HUTHNANCE (1982a), HUTHNANCE (1982b), DE VRIEND (1990) and HULSCHER et al. (1993) demonstrate the plausibility of a purely tidally origin of sandbanks.

In the light of a continuing sea-level rise, a thorough understanding of the wave climate seems to be of paramount importance. As demonstrated by MACDONALD & O'CONNOR (1996), a 10 % increase in wave energy can be expected by the year 2130, if the sea-level continues to rise at its present rate. If the sandbanks become less efficient as dissipators of wave energy, the wave pattern along the coast may alter; this may result in an intensification of coastal erosion.

From this, it may also be concluded that any significant change in the morphology, as well naturally as anthropogenically, may alter the existing patterns of areas where the wave energy is focussed or not, hence influencing the coastline configuration (HESP & HILTON (1996); MACDONALD & O'CONNOR (1996)).

6.6. Discussion and conclusions

The multiscale approach including the estimation of short-, medium- to long-term sediment transport, allowed a better understanding of morphological changes in the coastal zone. These findings have been supported by sediment transport calculations (Chapter 4) and can be interpreted and evaluated spatially (Chapter 5).

From the temporal grain-size variations, the mechanism whereby sediments are enriched along the slope of the swales, winnowed and transported along the slope of the sandbank and subdued to wave winnowing in the shallowest zone could be confirmed. As these processes seem to be valid throughout the seasons, they can be considered important for the maintenance of the banks, and indicate that the sandbanks are active in the present hydrodynamic regime. The sedimentological evidence suggests that along the sandbanks reworking of the surficial sediments is intense. The characteristics of the swale sediments show intermittent reactivation.

The relative scarcity of bedforms in the near coastal area is mainly attributed to its shallowness. Although the conditions for dune development could be met (ASHLEY (1990)), it is merely the time span needed for its development which is lacking. Moreover, the disperse character of wind-driven waves, especially in the areas shallower than - 7.5 m, may disable the formation of dune-like structures. Still, as mainly outlined in the previous chapter, larger scale bedforms do exist, but are confined to areas witnessing a specific hydrodynamic regime.

From the observed medium-term morphological changes along the Baland Bank, it is shown that this area resembles a high-energy depocentre witnessing mainly a high tidal current energy. In that sense, the sandbank can be regarded dynamic, though its morphology is fairly stable. Major events only induce a minor realignment of the bedforms. Through the Westdiep swale, the sandbank seems to have a direct sand supply for subsequent regional distribution. As hypothesised by HARRIS & JONES (1988), it seems plausible that sand supplied to the study area is first received by such dynamic banks, and is then dispersed among less mobile and immobile sandbanks through ebb- and flood-dominant zones of net sand transport.

Interesting is the observed accretional trend that is found after a period of stronger SSW to SW winds. This pattern is also found along the southern part of the Middelkerke Bank and the Ravelingen. As such a wind direction is aligned with the main axis of the tidal currents and the general configuration of the swales, it is believed that the latter act as a main conduit of sediment transport. It is thought that the sand supplied to these environments is just recirculated, though the nearshore zone, west of the study area may be regarded a source of sediments.

Adversely, no significant sediment input is expected from a NE direction. This can be supported by:

- observations preceded by NE conditions generally witness erosion; moreover, the associated sediment volumes are minimal;
- along the interaction zone with the Flemish Banks, areas that parallel the ebb-dominated swales, only recover slowly from erosion caused by NE winds; this contrasts with the areas in close interaction with the flood-dominated swales and thus having a direct sediment supply;

- side-scan sonar observations after a period of longer term NE winds merely reflect a lag surface, whilst the other situations merely indicate a deposition of suspended load, partly blurring the observations;
- also the sedimentary structures revealed by boxcoring show only minor laminations; this is in favour of a fairly homogeneous and stable sediment source.

Still, the hydrodynamic forces associated with the ebb tidal current are of paramount importance for the maintenance of the sandbank systems. That these forces should not be underestimated is shown by the typical morphology of the four subenvironments, each having a zone that is modified in the direction of the ebb tidal current.

Considering the morphological evolution throughout the study period, a general positive budget trend is found. From the chart differencing maps, the swales seem to be rather stable, whilst the shallower zones show a small shift of the bedforms. However, considering the volume variations, a clear increase is found. It should be stressed that the morphological evolution of the four subenvironments, remains a reflection of the processes active in the near coastal area. Although similarity exists with the nearshore and beach system, care should be taken in extrapolating the results. Still, it should be noted that the Baland Bank area was only mentioned on the hydrographic maps around 1924-1929 (VAN CAUWENBERGHE (1971)). DE MAEYER & WARTEL (1988) noted a minimal depth value of - 5.8 m, whilst in this study a most shallow point of - 2.8 m was found. Also, on the official hydrographic maps (BAZ 29/01/98) a depth correction to - 3.2 m was introduced. Hence, it is not clear to what extend the Baland Bank area is in equilibrium with the present-day sand supply.

From the sediment distribution in the near coastal area, sediments are transported in a northeastern direction. However, this migration direction can not be extrapolated to the sandbanks, that are quite stable features (VAN CAUWENBERGHE (1971)). It is believed that any migration would be counteracted by the strong tidal currents in the swales. From the internal reflectors merely a coastwards migration would be suspected. Such a migration would be enhanced by the wave orbital movement. This contrasts to the shoreface-connected ridges off the Holland coast, that are thought to migrate in a seaward and northeastward direction at a rate in the order of 0.5 to 1 m per year (VAN DE MEENE (1994)). Along the French coast TESSIER et al. (1996) mention a migration rate of 1 to 5 m/yr in a coastward direction.

Although only a hypothesis can be put forward regarding the origin of the sandbanks, it seems likely that the presented evidence mainly pleads for a formation of the sandbanks by modern processes.

In that perspective, it can only be stressed that an anthropogenical disruption of the morphodynamical equilibrium of a coastal system must be avoided as this may cause significant erosion along the coast. As shown in the present study, it is indeed of paramount importance that the processes acting in the coastal system are not disrupted because they are the mechanisms of which the longer term morphodynamical behaviour is dependent. It has been demonstrated that regardless of severe storms, the coastal system is characterised by a quick recovery, mainly due to a slow, but steady sand supply to the area. As the morphodynamical system seems to be self-regulating, caution is needed when one of the components is altered.

The general configuration of a coastal system is hence of primary importance to understand erosion and accretion phenomena. Only in that perspective, a deduction of the depth of closure, or the extend to which sediment transport is important, can be made (WRIGHT (1995)).

7. SYNTHESIS AND CONCLUSIONS

7.1. Synthesis

Shallow-marine environments are believed to be characterised by a dynamic response to changes in sea-level, wave climate, tidal currents and sediment availability (NIEDORODA et al. (1984)). This is especially the case for the shoreface and beach environment as these are specifically related to changes in wave energy (VAN ALPHEN & DAMOISEAUX (1989)). Still, it is merely the configuration of the offshore part that is often responsible for the wave energy pattern along the coast (MACDONALD & O'CONNOR (1996)). The dynamics of a sedimentary environment is complex and vulnerable to changes. Hence, its behaviour and interaction of processes can only be studied if a multidisciplinary approach is followed (Chapter 1). This can not be achieved by a single study; still it may form the basis for further research.

In the framework of the present investigation, it was aimed at distinguishing regional and local processes, responsible for the maintenance of the sandbank – swale system and this over different spatial as well as temporal scales. Moreover, as outlined in SWIFT et al. (1991) it was preferred to study the coastal area as a dispersal system whereby the regional context of sandbanks is considered within a sand transport system. Hence, a distinction is made with the hydrodynamic approach that merely deals with local processes on an event scale.

As demonstrated in Chapter 2, coastal systems are indeed complex sedimentary environments as they may reflect a variety of processes, not only naturally, but also anthropogenically induced. The Belgian coastal zone is generally characterised by semi-diurnal tides of macrotidal range. The direction and velocities of the tidal currents for a spring and neap tidal cycle strongly reflect southwest - northeast oriented rectilinear currents with ebb peak velocities on average 39 % smaller than those at flood tide. Most peculiar is the presence of a mud plume extending from the river Westerschelde up to Oostende and hydraulically trapped within the coastal zone.

The sediment- and morphodynamics of the coastal system was studied by means of a variety of sedimentological and geo-acoustical techniques (Chapter 3). Chronosequential measurements allowed the study of the evolution of the coastal system in time.

On the basis of current meter data, albeit confined to the navigational channels but spread over the area, the sediment transport capacity of the flow was calculated (Chapter 4). Given the rather fine sediments in the near coastal area, suspended load mostly accounted for more than 90 % of the total load. From this, it could be deduced that even under the influence of currents alone, sediments are likely resuspended in the swales. Grains of 210 µm are easily transportable over the area whilst coarser grains can only be entrained in the swales witnessing the highest current velocities. Especially the Westdiep swale has a high sediment transport capacity, hence acts as the major conductor of sediments. From the calculations under the combined action of currents and waves a reversal of the bedload transport in a southwestern direction can be initiated.

The results presented in Chapter 5 contribute to the present knowledge on the reworking of modern shelf environments. Especially in an environment where tidal- and wind-driven currents as well as wind waves are important, it is often difficult to unravel the processes involved (DALRYMPLE (1992)).

Although the presence of larger-scale bedforms seems at first unlikely in a rather shallow marine environment, large to very large dunes could be distinguished. Their occurrence was merely confined to areas witnessing higher dynamics. Most peculiar are the dune-like structures in the Baland Bank area that reach heights of up to 3 m. Also along the western extremity of the Stroombank and along the slope of the Westdiep swale, large to very large dunes were recognised.

On the basis of a detailed set of boxcores, the sedimentary pattern is mainly controlled by the combined action of currents and waves. The swales are predominantly bioturbated and are characterised by a mixture of sediments, whilst the upper layer of the sandbanks is merely homogenised by the combined action of currents and waves. In the Westdiep swale, south of the Flemish Bank area, older relict sediments seem to be reworked by the present hydraulic regime.

The surficial sediments of the near coastal area are mainly characterised by fine (125-250 µm) to very fine (62.5-125 µm) sands. Still, medium sands occur in the areas witnessing an intense tide-topography interaction. Striking is the correlation with the presence of bedforms. As well from the bedform evidence as from the sedimentary pattern and the surficial grain-size characteristics, it is clear that generally only the area shallower than - 8 m is frequently reworked. Deeper, hardly any bedforms can be observed and the surficial sediments become finer and more poorly sorted. Moreover, the sediments are most likely to be enriched with mud, possibly deposited from the surficial waters during the turning of the tides. Deposition of mud may even occur somewhat deeper than - 6 m, except for areas with higher dynamics due to their configuration.

From a fraction analysis of the sediments, a succession of processes could be deduced. An interactive model is proposed whereby sediment transport is mainly dependent on the swale configuration. Especially when tidal currents are funnelled, sandy deposits are being washed out towards the slopes of the banks. Part of the accumulated sediments is subsequently winnowed out and transported upslope the sandbanks, whereby the fining upwards trend is mainly tidally driven. In water depths shallower than - 5 m, waves play an important role, washing out the fines and entraining the coarser fraction, which is ultimately deposited along the steep slope. Since the current velocity in the swales is competent enough to transport sediments, any landward migration of the banks would be counteracted by the transport capacity within the swales.

In time, the above mentioned observations and interpretations can be confirmed (Chapter 6). Generally, the Belgian coast can be classified as a mixed environment characterised by both strong tidal currents and moderate wave conditions.

The succession of processes, as deduced from the surficial grain-size characteristics, seemed to be valid throughout the seasons. This is merely a result of the intense hydraulic sorting processes active in the area. Most striking is the more coarser sediment texture that is representative of calmer periods, whilst a reverse trend is seen under rougher conditions. During the summer months no coarser grains are actively transported; this is reflected in an abundance of such grains in the sediment. Finer grains seem to be depleted as they can be transported by the hydrodynamic agents. Still, there is no active transport, hence those fractions are not renewed. During the winter months, coarser fractions are depleted due to an entrainment by the enhanced hydrodynamic forces. Wave stirring and advection by the combined action of currents and waves are the dominant sediment transporting sediments. Finer grains are actively winnowed out and transported. Moreover, they are easily replenished. The coarsest grains occur in the swales, the main conductors of sediment. The abundance of coarse grains in the swales is highest during the winter months, meaning that a lot of sediment can be advected. Correlating the observations with the variations in hydrodynamical and meteorological conditions learns that sediment transport is intense when the meteorological forces align with the tidal currents. Most deviation is seen when persistent N to NE conditions preceded the observations. Under these conditions, the surficial sediments merely reflect lag deposits and it seems that only the finer fraction is redistributed.

The sediment transport capacity was also evaluated on the basis of crestline displacements of the large to very large dunes. Generally, the similarity is more striking than the differences. Only minor modifications occurred between the successive campaigns. Although, the bedforms adjust to the ruling hydro-meteorological conditions, their main body remains flood-dominated. Still, one campaign witnessed a reversal of the bedform asymmetry. The preceding conditions corresponded with persistent NE winds of only moderate force.

From height difference maps between the successive campaigns and quantified by volume calculations, an indication of the vulnerability of the coastal system can be given. The evidence is mainly confined to the Baland Bank area, but is also supported by the observations along the southern part of the Middelkerke Bank and the Ravelingen. From this, it can be stated that there is a clear relation between the observed morphological changes and the ruling hydro-meteorological conditions. In terms of gain and losses, the volume variations along the Baland Bank show that the lowest volumes are generally associated with summer to autumn conditions, whilst the winter months witness the highest volumes. The sediment volumes in the spring period likely fall within the range of both.

As was already expected from the sedimentological findings, N to NE winds are associated with the lowest sediment volumes, whilst a significant increase is seen for SSW to SW conditions. Sediment transport is indeed most intense when the direction of storminess parallels with the configuration of the swales. From the observations, it can also be deduced that the duration of stormy conditions is more important than the strength. Moreover, the sedimentary pattern in the near coastal area is characterised by a quick recovery after stormy periods.

Although no real evidence could be presented concerning the long-term evolution of the coastal system, some hypotheses are put forward on the formation of the sandbank – swale system. Throughout the Holocene transgression, the area evolved from roughly a tidal flat to a fully marine environment. The sediments found in the near coastal area, represent both the fossil and modern environment. Given the sediment transport potential, also the older sediments can be reworked by the present hydraulic regime. The Coastal Banks are thought to be formed by modern processes similar to those building up the shoreface-connected ridges off the Holland coast (VAN DE MEENE (1994)). Their origin is likely constrained to a time period having hydrodynamic characteristics comparable to the nowadays situation. Hence, a classification as storm-dominated ridges (SWIFT (1975)) seems not really appropriate.

Indeed, from the mobility of the seabed sediments in response to the tidal currents, it seems that the development of the banks is not dependent on storm wave activity nor on storm-driven currents. Also, the field of existence and asymmetry of bedforms are influenced by tidal, rather than storm-induced currents. The fact that the banks are quasi feature-less and at some locations round-crested is merely a consequence of wave activity. From this, it seems more plausible to consider them as tidal-current ridges as described by OFF (1963).

Generally, it may be concluded that any significant change in the morphology, as well naturally as anthropogenically induced, may have significant effects on the adjacent coastline. As well from the observations presented by VAN CAUWENBERGHE (1971), LIGTENDAG (1990) as from the numerical modelling of MACDONALD & O'CONNOR (1996), it can be deduced that a disruption of the morphodynamical equilibrium of the coastal system may have a significant impact on the coastline configuration.

7.2. Discussion

From the evidence presented throughout this study, some of the research questions, outlined in Chapter 1, have been answered, others can be viewed in a broader perspective.

7.2.1. Onshore – offshore sediment exchange?

As no interactive offshore – onshore study has been carried out, no conclusive evidence is available on the importance of cross-shore sediment transport. Still, some arguments can be put forward.

From the evidence presented throughout the chapters, it seems that the tidal currents are the primary agents of sediment transport. Their strength determines the sediment transport potential and the hydraulic sorting processes, responsible for the build-up of the major sandbanks. As the Baland Bank, lies within an active sediment transport pathway, its morphological behaviour reflects the dynamics of the area. The temporal variability of this area shows that the near coastal area is especially vulnerable to NW-N-NE conditions, whilst SW winds are merely associated with an input of sediment and an enhancement of the hydraulic sorting processes. As the area is hardly disrupted by frontal waves, and is characterised by a fairly quick recovery, it seems acceptable that the morphological behaviour of the coastal system is determined by the tidal currents. From this, it seems also likely that the longshore component of the sediment transport strongly overrules the cross-shore component.

Studying the sediment dynamics in the Flemish Bank area, VAN VEEN (1936) concluded that there was no significant sediment transport. However, he noted that the beaches do show a net sand transport in a northeastern direction. Observations confirm such transport directions on the high beach (BASTIN (1974), mainly due to the dominance of southwestern to western winds and the combined wave directions. Where swales approach the coast (west and mid coast), tidal currents can enhance this effect.

Authors as BASTIN (1974) put forward the importance of muddy sediments as a destabilising factor in the cross-shore transport. It is believed that the sand may be trapped by the finer fractions. Indeed, the Kleine Rede is characterised by muddy sediments that likely hamper an active offshore - onshore sediment exchange . West of Nieuwpoort, the sandbank – swale system "Broersbank" - "Potje" (Fig. 1.01) has an active connection with the beach and is more likely to exchange sand with the beach. However, the tidal currents in the flood dominated swale "Potje" are funnelled and also cause coastal erosion.

DE MOOR (1996) confirms this hypotheses, but also put forward that west of Nieuwpoort accretional beaches are combined with a muddy nearshore. Hence, the net sand supply occurs rather alongshore, and the impact of waves upon the long-term evolution of the beaches should not be overestimated.

The results of this study have shown that there is a unique balance between the strength of the tidal currents, the sediments to be transported and the combined action of currents and waves. It is believed that as well along the sandbanks as along the shoreface, an enrichment of sediments occurs at the lower foot of the morphological entities, that part of this sediment buffer is gradually deposited along the slope and that finally the combined action of currents and waves entrains the sediment in a shorewards direction. This process is most likely to occur under SW winds. These conditions gradually bring in sediment and the currents are strong enough to maintain this upbuilding process. However, if the tidal currents are strongly enhanced, this process may result in an eroding process along the slope, but possibly associated with a deposition of sediment along the beach. This mechanism could explain the alternation of an erosive shoreface in combination with an accretional beach as observed by CORBAU et al. (1999), east of Dunkerque.

Adversely, under severe storm conditions, the beach sediments may be depleted and carried offshore. It is believed that the eroded sand is reorganised along the foot of the sandbanks or the shoreface, and will be swept by the tidal currents, rebuilding the sedimentary environment. This mechanism pleads for the feeder berm system as soft beach protection works. However, if the storminess persists over a long period and the tidal currents are largely enhanced, large quantities of sediment may indeed be lost.

7.2.2. The role of the sandbank – swale system in coastal erosion?

This research question is partly discussed in the previous paragraph. Generally, the relation sandbank – coast is two-fold: on the one hand sandbanks protect the coast as they dissipate and refract wave energy; on the other hand sandbanks close to the coast might have a funnelling effect on the current leading to coastal erosion. In some cases, the coast acts as a sediment source for the banks or vice versa. In the latter case, the banks help in stabilising the beaches.

However, more importance should be given to the study of a coastal system as a whole. It seems of paramount importance to determine the interrelations between sandbanks and swales on the one hand and sandbanks, swale, shoreface and beach on the other hand.

The interactive zone of mutually evasive flood- and ebb-dominated channels is a vulnerable area, and a breakthrough of the system is likely to cause significant changes in the sediment dynamics. This could also be observed on the map of VAN CAUWENBERGHE (1966), studying the bathymetric changes of the Schelde estuary in the period 1799 - 1968. Before equilibrium is reached again, the area will be rather unstable. Moreover, ebb- and flood-dominated zones can evolve through time, and are considered to link sediment source and depositional areas (HARRIS & JONES (1988)).

If major storm events (on a decennial basis) significantly alter the sandbank – swale system and induce a disequilibrium in the coastal system a normal recovery may be disabled hence leading to a retreat of the coastline.

It seems however more likely that anthropogenic influences would alter the coastal system. If major changes are induced (i.e. sand mining) the wave characteristics may be altered giving rise to different wave refraction patterns which in turn cause a different erosion – accretion pattern. Moreover, engineering works may cut off a normal sand supply decreasing the recovery rate of a coastal section.

7.3. Conclusions

From chronosequential sedimentological and geophysical evidence, the Belgian coastal zone west of Oostende can be considered a unique depositional environment, witnessing an interplay of different physical processes superimposed by external forces.

The area is clearly influenced by the presence of strong flood- and ebb-dominated swales of which the interaction gives rise to zones of net sand transport. Most peculiar is the presence of a small sandbank, the Baland Bank and an adjacent dune field, which can be considered a high-energy depocentre. The sensitivity of this area is intensively investigated in relation to other zones situated further offshore, in order to study possible sediment exchanges. To a certain extend, it can be sustained that sand supplied to the coastal system is first received by dynamic banks such as the Baland Bank, and then dispersed among lesser mobile sandbanks such as the Nieuwpoort Bank and the Stroombank.

From the spatial variability, it seems that shallower than roughly - 8 m, the water movement, the sand transport and the morphology are in continuous interaction, hence indicative of a morphodynamically coupled system. The intense hydraulic sorting processes under the combined action of currents and waves especially prove this; the latter mainly stir up the sediment, whilst the tidal currents actively transport the sediment.

In order to comprehend the ruling sedimentary fluxes and causal relationships, the sedimentological and geophysical database is coupled to variations in hydrodynamical, maregraphical and meteorological parameters.

It is put forward that the coastal system is characterised by a quick recovery. SW winds are associated with an input of sediment, whilst the frontal winds merely cause erosion. The long-term effect is however dependant on the duration of the active forces.

Regardless of the wide spatial and temporal variability of the sediment movements and the diversity of the processes acting along the coastal system, a mechanism is identified whereby the different subenvironments can be linked. The variability most probably has a longshore and cross-shore component, though the latter seems to be inferior due to the strong tidal currents in the area. Still, a mechanism is proposed explaining the cross-shore sediment distribution.

Although the variation in wave energy is thought to be the key to explain alternating zones of erosion and accretion along the coast, their influence could not be determined and yet needs further investigation. The distribution of the wave energy pattern is moreover determined by the presence of the sandbanks. This means that any major change in the morphology or dynamics of this system may have an effect on the long-term development of the coast.

From the evidence, it can only be emphasised that a monitoring of the western part of the Belgian coastal zone at different time scales leads to a better confining of process-response models, and enables the understanding of coastal erosion and accretion phenomena in a broader sediment-dynamical framework.

7.4. Recommendations for future research

The evidence presented throughout the chapters can be used to evaluate natural and man-made changes to a coastal system. The volumetric calculations can be further quantitatively and statistically assessed, and presented in terms of the regional and local conditions, i.e. storm history, seasonality, wave climate, man-made environmental and engineering changes, and large- and small-scale landforms (GORMAN et al. (1998)). Moreover, it would be interesting to hydrodynamically justify the observations.

As demonstrated along a variety of coasts, it seems worthwhile to investigate the relation between wave patterns and coastal erosion and accretion (WRIGHT et al. (1991), BRAY et al. (1995)). This may perhaps lead to a definition of littoral cells that may aid the management of the coastal zone. As demonstrated by CORBAU et al. (1999) such delineation should also be carried out along the shoreface and perhaps also further offshore. This will facilitate the understanding of the exchange mechanisms between the different environments. Still, it needs emphasis that the coast is heavily groyned; hence artificially induced morphological changes may overrule the natural variability.

A better understanding of the relationships between inner shelf, shoreface and beach processes in relation to hydrodynamical and meteorological conditions is a research topic that is timeless. The better estimation of the sediment budgets involved in the coastal zone, the better coastal erosion and accretion can be evaluated, and the better coastal zone management plans can be carried out. Still, "*as life is full of its little ironies*", one can only attempt to improve its understanding of the behaviour of a coastal system through time. Hence, it seems appropriate to conclude referring to BAUER et al. (1996):

"*Accepting indeterminacy implies accepting uncertainty, and this suggests developing research strategies that explore and quantify natural system variability*".

8. DUTCH SUMMARY – NEDERLANDSTALIGE SAMENVATTING

De Belgische kustnabije zone wordt gekenmerkt door een aantal zandbanken die nagenoeg parallel aan de kust verlopen. De belangrijkste morfologische entiteiten die in de huidige studie aan bod kwamen zijn de Stroombank en de Nieuwpoort Bank, beide gecontoureerd door de - 5 m dieptelijn. Gezien de geringe waterdiepte, hebben ze slechts een weinig uitgesproken morfologie. In het bijzonder is echter de sediment- en morfodynamiek bestudeerd van de Baland Bank, een jonge zandbank, ingesloten door de Stroombank en de Nieuwpoort Bank en in directe interactie met de Westdiep geul. Teneinde de processen in zo'n ondiep-water gebied beter te begrijpen, werd bovendien een vergelijkend onderzoek verricht langsheen de zuidelijke rand van de Middelkerke Bank en de Ravelingen, beide behorende tot het systeem van de Vlaamse Banken.

De hydrodynamiek in het gebied is voornamelijk bepaald door een halfdagelijks macrotidaal getijdesysteem waarbij de eb-piekgetijdestroming ondergeschikt is aan de vloed-piekgetijdestroming. Dit impliceert in hoofdzaak een noordoostwaarts gerichte residuele stroming. De kustzone wordt bovendien gekenmerkt door een sedimentpluim, hydraulisch gevangen door residuele getijdestromingen en de kustwaarts gerichte orbitale golfbeweging.

Teneinde het sedimentologisch en morfologisch gedrag van het kustsysteem te bepalen, werd een geïntegreerde onderzoeksmethodologie opgesteld en dit zowel voor verschillende ruimte- als tijdschalen. Chronosequentiële sedimentologische en geo-akoestische metingen lieten toe de evolutie van de meest dynamische zones te onderzoeken.

Op basis van bestaande stroommetergegevens werd vooreerst het sediment transport potentieel in het studiegebied berekend. Hieruit bleek dat de getijdestromingen competent genoeg zijn om het *in-situ* sediment in beweging en in suspensie te brengen. De geulen, vooral het Westdiep, kunnen door hun kanaliserend effect een belangrijk aandeel van sediment aanvoeren. Uit de sedimenttransport-berekeningen bleek dat korrels van 210 µm transporteerbaar zijn over het gehele gebied, terwijl de Westdiep geul sedimenten tot 400 µm kan transporteren. Algemeen gezien neemt het suspensief transport tot meer dan 90 % van het totale sedimenttransport voor zijn rekening.

De ruimtelijke en temporele observaties in de meest dynamische zones doen een gekoppeld morfodynamisch systeem vermoeden; m.a.w. de waterbeweging, het zandtransport en de morfologie zijn in een continue interactie. Dit is voornamelijk aangetoond door de actieve sorteringsprocessen (stromingen en golven) die het sedimentpatroon op de banken bepalen. Algemeen gesteld, zijn de kustbanken morfologisch slechts weinig uitgesproken. De ondiepte van het milieu impliceert een verhoogde golfwerking waardoor de opbouw van bodemstructuren verhinderd wordt. Toch kon de aanwezigheid van grote tot heel grote (> 3 m) duinstructuren op een aantal plaatsen worden aangetoond. Hun voorkomen is gecorreleerd met zones die door hun unieke configuratie een verhoogd dynamisme kennen.

De sedimentaire opbouw van het zandbanken – geulen systeem, werd onderzocht door het aanwenden van boxcores. Hieruit bleek dat de geulen opgebouwd zijn uit een waaier van sedimenten en schelpenmateriaal, terwijl de verticale opbouw van de zandbanken een vrij homogene textuur vertoont. Dit is voornamelijk te wijten aan de gecombineerde actie van golven en stromingen. De geulsedimenten zijn meestal sterk aangerijkt met slibbige sedimenten. Algemeen gesteld, kan een sedimentatie van slib verwacht worden in zones dieper dan - 8 m. Ondieper dan - 6 m wordt geen slib meer aangetroffen. In de Westdiep geul ten zuiden van de Vlaamse Banken worden bovendien relicte sedimenten omgewerkt door het huidige hydraulische regime.

De oppervlakkige sedimenten van het kustnabije gebied zijn vooral gekenmerkt door fijn (125-250 µm) tot heel fijne (62.5-125 µm) zanden. Zanden met een korrelgrootte grover dan 250 µm zijn beperkt tot zones met een verhoogde zeebodem – getijde interactie. Opmerkelijk is de correlatie van deze zanden met het voorkomen van grotere bodemstructuren.

Uit een fractie analyse van de oppervlakkige sedimenten kon een interactief model worden voorgesteld ter aanduiding van het behoudsmechanisme van het zandbanken – geulen systeem. Hieruit bleek dat de grofste sedimenten zich bevinden aan de basis van de zandbanken, resulterend uit een aanrijkingsproces vanuit de geulen. Deze sedimentbuffer wordt hydraulisch gesorteerd en geleidelijk hellingopwaarts getransporteerd door het getij. Ondieper dan nagenoeg - 5 m, is gemiddeld de golfactie echter ook belangrijk. Grovere korrels kunnen actief getransporteerd worden, terwijl de fijnere in-suspensie-gebrachte fracties uitgewassen worden. De vergrovende trend is merkbaar tot ruwweg halverwege de steile helling.

Windaangedreven stroming is belangrijk in de kustzone. Seizoenaal blijkt dat tijdens de winterperiode de sedimenten fijner en slechter gesorteerd zijn; de variatie tijdens de zomermaanden is algemeen gesteld significanter. Dit kan vertaald worden in een transport van zowel grovere als fijnere korrels onder ruwere condities en veroorzaakt door golfopwoeling en advectie door getij- en of windgedreven stromingen. Gezien de fijnere fracties actief getransporteerd worden, hebben zij een hoog afzettingspotentieel. Onder kalme omstandigheden is het sedimenttransport meer intermitterend en wordt enkel de fijne fractie herverdeeld. De processen aan de basis van het behoud van de zandbanken bleken geldig onder veranderende weersomstandigheden en dit tevens voor de strandsedimenten.

Het sediment transport potentieel werd tevens geëvalueerd aan de hand van de verschuivingen van de kamlijnen van de grote duinstructuren. Vooral in het Baland Bank gebied dat toch gekenmerkt is door een intense interactie van de hydrodynamische agentia met de zeebodem, was de stabiliteit van de structuren opmerkelijker dan de verschillen. De bodemstructuren passen zich wel aan aan het hydraulisch regime, maar zelfs na sterke stormen bleef de globale morfologie nagenoeg ongestoord. Dit is mede bewerkstelligd door de intense hydraulische sorteringsprocessen.

Uit hoogteverschilkaarten van de opeenvolgende campagnes in combinatie met volumeberekeningen kon het sedimentologisch en morfologisch gedrag van de meest dynamische zones bestudeerd worden. Algemeen gesteld komen de laagste sedimentvolumes overeen met zomer en herfst condities, terwijl de wintermaanden het hoogste volume vertonen. Versterking van de getijdestroming door meteorologische invloeden in een zelfde richting verhoogt aanzienlijk het sedimenttransport (vooral de vloedstroom in combinatie met langdurige zuidwestenwinden). Na storm periodes kent het Baland Bank gebied dan ook een algemene ophoging, wat bevestigt dat de geulen actief sediment kunnen transporteren. N tot NE condities zijn echter geassocieerd met lage sedimentvolumes. Uit de temporele metingen bleek tevens dat de duur en de uniformiteit van de meteorologische factoren primeert boven hun sterkte. Veldobservaties tonen aan dat significant bodemtransport in een zuidwestelijke richting kan optreden na langdurige noordoostenwinden, zelfs van gematigde kracht (5-6 Bf). Dit kon bevestigd worden door de sedimenttransportberekeningen.

De vloedstroom kan dus beschouwd worden als een belangrijke sedimentaanvoerder, terwijl de ebstroom eerder een vormgevend belang heeft. Dit betekent een verhoging van zowel het suspensief als bodemtransport tijdens de vloed, terwijl tijdens de eb hoogstwaarschijnlijk het bodemtransport domineert.

Algemeen gezien, kent het gebied een vlug herstel; de hydraulische sorteringsprocessen zijn dan ook intens.

Uit de spatiale en temporale differentiatie van het kustsysteem blijkt dat het sedimenttransport langsheen goed afgelijnde transportpaden verloopt. Het sediment transport potentieel van de geulen is hierbij van groot belang gezien zij de bron- en de afzettingsmilieus met elkaar verbinden. De nabije kustzone is dan ook aanzien als een auto-regulerend sediment transport systeem waarbij een transversaal transport ondergeschikt is aan het kustlangse transport.

De processen geïdentificeerd in de nabije kustzone, bleken tevens van kracht langsheen de zuidelijke rand van de Vlaamse Banken. De onderzochte gebieden getuigden echter niet alleen van een convergentie van stromingen, maar tevens van sedimenttransport. Een uitwisseling van sedimenten tussen de Vlaamse Banken en de nabije kustzone lijkt echter ondergeschikt aan het kust parallelle transport gestuurd door de geulen.

De zandbanken hebben een polygenetisch karakter; evenals de Vlaamse Banken zijn de kustbanken opgebouwd in verschillende fases. Ondanks dat de interne reflectoren van de kustbanken een kustwaartse migratie doen vermoeden, wordt deze tendens tenietgedaan door de sterke stromingen in de geulen; dit verklaart hun relatieve stabiliteit.

Alhoewel geen bijkomende bewijzen zijn aangebracht ter ondersteuning van de kustevolutie op langere termijn, zijn toch een aantal hypotheses geopperd omtrent de evolutie van het kustsysteem. Verwijzend naar de kustaangehechte banken langsheen de Hollandse kust (VAN DE MEENE (1994)), lijkt het tevens aannemelijk dat de kustbanken gevormd zijn onder een hydraulisch regime gelijkaardig aan het hedendaags systeem. Vooral de accretionele trend van het Baland Bank gebied lijkt te kaderen in het herstel van een morfodynamisch evenwicht, nadat het oostelijke uiteinde van de Stroombank gebaggerd werd ten voordele van een navigatiekanaal naar de haven van Oostende.

De relatie met kusterosie kan op basis van een 4-jarige tijdsreeks moeilijk aangetoond worden; wel is het duidelijk dat de functie van de zandbanken als natuurlijke kustprotectie moet gevrijwaard blijven, zeker in het licht van de globale zeespiegelstijging.

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Appendix A

Procedure for the prediction of transport rates under the combined action of currents and waves *(based on Soulsby 1997)*

Error estimates (including sensitivities) are indicated as % variability (Soulsby 1997)

Background information required:
- bathymetry and water depths;
- sediment type and mobility;
- current speed and direction; and
- wave climate

Water properties
- as the tidal range is significantly high, the real depth above the current meter stations is taken into consideration;
- temperature and salinity are respectively taken as 10° C and 35 ppt;
- water density = 1027 kg/m^3, kinematic viscosity = 1.36 10^{-6} m^2/s (1 % variability); and
- gravity = 9.81 m/s^2

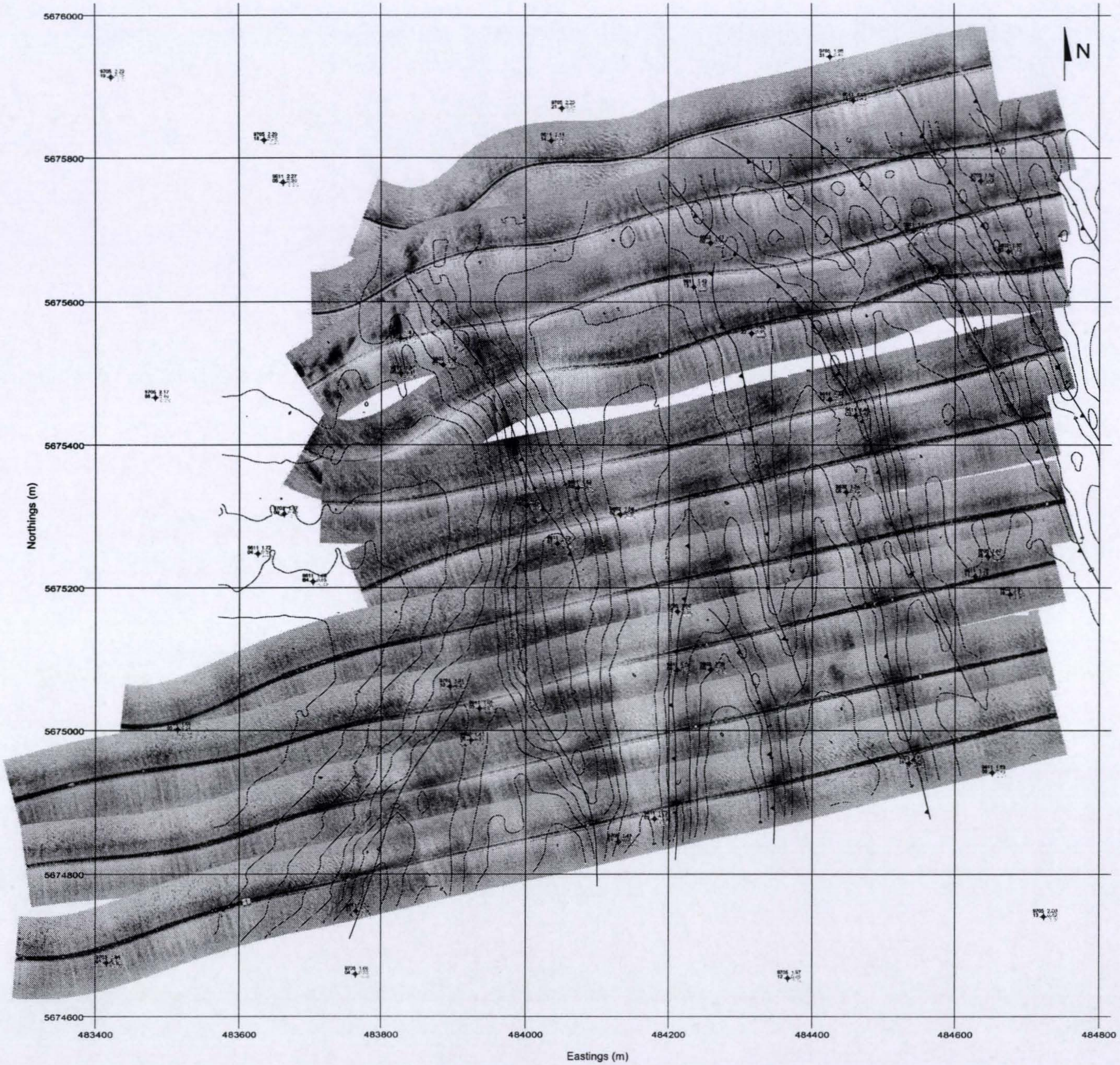
Bed material
- d10, d16, d35, d50, d65, d84, d90 (grain diameter for which respectively 10, ..., 90 % of the grains is finer);
- density of the sediment: 2650 kg/m^3 for quartz grained beds (caution if >30 % of the sediment are shells);
- calculation for d=d50;
- dimensionless grain size D_*;
- threshold Shields parameter θ_{cr};
- threshold shear-stress τ_{cr};
- settling velocity w_s (10 % variability); and
- sloping bed effects

Combined waves and current:

- joint probabilistic distribution of currents and waves;
- measurements of current speed;
- wave characteristics for monochromatic or a spectrum of waves (height, period, direction, bottom orbital velocities) (10 % variability);
- mean (τ_{ms}) and maximum (τ_{maxs}) values of the skin-friction bed shear-stress over a wave cycle and conversion to mean (u_{*ms}) and maximum (u_{*maxs}) friction velocities and mean (θ_{ms}) and maximum (θ_{maxs}) Shields parameter (20 % variability)

if $\theta_{maxs} < \theta_{cr}$	: immobile bed (assume rippled)
if $\theta_{cr} \leq \theta_{maxs} \geq 0.8$	: mobile and rippled bed
if $\theta_{maxs} > 0.8$	: mobile bed and flat with sheet flow
if $u_{*maxs} \leq w_s$	: no suspension
if $u_{*maxs} > w_s$	: suspension

- height and wavelength of current ripples and wave ripples (the largest are selected);
- effective total roughness z_o, from the ripple dimensions;
- mean (τ_m) and maximum (τ_{max}) values of the total bed shear-stress over a wave cycle and conversion to mean (u_{*m}) and maximum (u_{*max}) friction velocities and mean (θ_m) and maximum (θ_{max}) Shields parameters: Calculation of τ_m enables to determine sediment diffusion ; τ_{max} the threshold of motion and entrainment rate of sediments (50 % variability);
- median suspended grain size and corresponding settling velocity, w_s ; suspended sediment concentration at desired heights (a factor of 3 variability under currents ; a factor of 5 under currents and waves);
- mean bedload transport rate;
- mean total sediment transport rate; and
- pattern of erosion and deposition



SIDE-SCAN SONAR MOSAIC
OF THE BALAND BANK AREA

(Belgian continental shelf)

GENERAL NOTES

Survey platform:	RV BELGICA
Positioning System:	Sercel DGPS NR 103
Side-scan sonar data acquired by:	KLEIN 595 - dual frequency transducer (100 & 500 kHz) Used frequency: 500 kHz
Data acquisition:	Delph software
Data processing:	Isis, Vista & Triport software (Triton Technology Inc.)
Depths:	in metres (datum: MLLWS)
Survey Date:	24-25/09/1996
Projection Type:	UTM - Zone 31

80 0 80
metres

LEGEND

Crestline of the large to very large dunes with an indication of the asymmetry
Depth contour line
Van Veen grab sample

Parameters
Campaign
Sample number
Mean
Sorting
Skewness

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